1938

LIBRARY
FISH & WILDLIFE SERVICE
PACIFIC OCEANIC FISHERY
INVESTIGATIONS

WOODS HOLE OCEANOGRAPHIC INSTITUTION

COLLECTED REPRINTS

1938

MARCH, 1939

WOODS HOLE OCEANOGRAPHIC INSTITUTION

COLLECTED REPRINTS

1938

1701

LIBRARY
FISH & WILDLIFE SERVICE
PACIFIC OCEANIC FISHERY
INVESTIGATIONS

MARCH, 1939

The present volume contains the contributions from the Woods Hole Oceanographic Institution which appeared during 1938 in publications other than *Papers in Physical Oceanography and Meteorology;* also the Annual Report of the Director.

TABLE OF CONTENTS

Contribution
No.

136. MARSHALL SCHALK
A Textural Study of the Outer Beach of Cape Cod, Massachusetts

147. HENRY B. BIGELOW
Plankton of the Bermuda Oceanographic Expeditions. VIII. Medusae taken during the Years 1929 and 1930

→ 152. H. R. SEIWELL and GLADYS EDDY SEIWELL
The Sinking of Decomposing Plankton in Sea Water and its Relationship to Oxygen Consumption and Phosphorus Liberation

154. FLOYD M. SOULE
Oceanography. Excerpt from International Ice Observation and Ice Patrol Service in the North Atlantic Ocean, Season of 1936

159. ALFRED C. REDFIELD and ANCEL B. KEYS
The Distribution of Ammonia in the Waters of the Gulf of Maine

160. SELMAN A. WAKSMAN, MARGARET HOTCHKISS, CORNELIA L. CAREY and Y. HARDMAN
Decomposition of Nitrogenous Substances in Sea Water by Bacteria

161. SELMAN A. WAKSMAN and UNTO VARTIOVAARA
The Adsorption of Bacteria by Marine Bottom

163. THEODOR VON BRAND
Quantitative Determination of the Nitrogen in the Particulate Matter of the Sea

165. SELMAN A. WAKSMAN and MARGARET HOTCHKISS
On the Oxidation of Organic Matter in Marine Sediments by Bacteria

166. GEORGE L. CLARKE
Seasonal Changes in the Intensity of Submarine Illumination off Woods Hole

167. ATHELSTAN F. SPILHAUS
A Bathythermograph

168. GEORGE L. CLARKE
Light Penetration in the Caribbean Sea and in the Gulf of Mexico

169. H. C. STETSON
Present Status of the Problem of Submarine Canyons

170. R. B. MONTGOMERY
Fluctuations in Monthly Sea Level on Eastern U. S. Coast as Related to Dynamics of Western North Atlantic Ocean

171. C. O'D. ISELIN
The influence of Fluctuations in the Major Ocean Current on the Climate and the Fisheries

172. BOSTWICK H. KETCHUM and ALFRED C. REDFIELD
A Method for Maintaining a Continuous Supply of Marine Diatoms by Culture

Contribution
No.

174. BENJAMIN B. LEAVITT
The Quantitative Vertical Distribution of Macrozoöplankton in the Atlantic Ocean Basin

175. NORRIS W. RAKESTRAW and VICTOR M. EMMEL
The Solubility of Nitrogen and Argon in Sea Water

176. J. H. WELSH and F. A. CHACE, JR.
Eyes of Deep-Sea Crustaceans II. Sergestidae

177. H. R. SEIWELL
Eddy Diffusion at Mid-Depths in the Caribbean Sea Region

179. ALBERT EIDE PARR
Further Observations on the Hydrography of the Eastern Caribbean and Adjacent Atlantic Waters

180. C. O'D. ISELIN
A Promising Theory Concerning the Causes and Results of Long-Period Variations in the Strength of the Gulf Stream System

181. H. R. SEIWELL
Use of Non-Conservative Properties of Sea Water to Physical Oceanographical Problems

182. NORRIS W. RAKESTRAW and VICTOR M. EMMEL
The Relation of Dissolved Oxygen to Nitrogen in Some Atlantic Waters

183. W. H. JOHNSON
The Effect of Light on the Vertical Movements of *Acartia clausi* (Giesbrecht)

185. C.-G. ROSSBY
On the Mutual Adjustment of Pressure and Velocity Distributions in Certain Simple Current Systems, II.

186. H. R. SEIWELL
Über die ganz- und halbtägige Mondkomponente der internen Wellen im westlichen Nordatlantischen Ozean

188. CORNELIA L. CAREY
The Occurrence and Distribution of Nitrifying Bacteria in the Sea

189. LOIS C. LILLICK
Preliminary Report of the Phytoplankton of the Gulf of Maine

198. W. J. CLENCH and C. G. AGUAYO
Notes and Descriptions of New Species of Calliostoma, Gaza and Columbarium (Mollusca); Obtained by the Harvard-Habana Expedition off the Coast of Cuba

200. PEDRO J. BERMÚDEZ
Resultados de la Primera Expedicion en las Antillas del Ketch Atlantis bajo los auspicios de las Universidades de Harvard y Habana

THE WOODS HOLE OCEANOGRAPHIC INSTITUTION
Report for the year 1937

LIST OF CONTRIBUTIONS

Contribution No. 136

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 8, NO. 2, PP. 41–54, FIGS. 1–2, AUGUST, 1938

A TEXTURAL STUDY OF THE OUTER BEACH OF CAPE COD, MASSACHUSETTS

MARSHALL SCHALK
Gulf Refining Company, Pittsburgh, Pa.

Contribution No. 136, Woods Hole Oceanographic Institution

ABSTRACT

In conjunction with the program of bottom sediment investigation in progress at the Woods Hole Oceanographic Institution, a series of samples of sand from the outer beach of Cape Cod, Massachusetts, were subjected to mechanical analysis. Study of the results of some 234 analyses indicates that the finest grained sand is within the cliff or source section. Both to the north and to the south in the wave-built sections the median diameters increase. The increase in the direction of drift was checked by a repetition of sampling in the cliff and northern wave-built sections the following summer. With the aid of evidence from near shore bottom samples, the unusual condition is shown to result from loss of finer grades in the material supplied by cliff cutting as longshore drift takes the material to leeward.

INTRODUCTION

The investigation had its beginning in an attempt to study by repeated samplings a small beach throughout a year's time. Before the collection of samples was finished on this project the writer had opportunity to work on the Cape Cod beach with the cooperation of the bottom sampling program of the Woods Hole Oceanographic Institution. Findings of the original study which was made on the shores of Ipswich Bay, Massachusetts, are to be published in a separate paper.

The outer beach of Cape Cod offers a long stretch of beach interrupted by few inlets. The supply of new material from the cliffs extending for almost fifteen miles allowed the hope of tracing this heterogeneously sized material as the waves distributed it along the coast. Furthermore, the exposures vary from the full sweep of the Atlantic to the comparatively moderate conditions within Cape Cod Bay. In addition, wide variation in the steepness of the foreshore is found.

H. C. Stetson, in charge of geological investigation at the Woods Hole Oceanographic Institution, first suggested the desirability of a mechanical study of the Cape Cod beaches. His advice and cooperation with related offshore samples have been of invaluable assistance throughout the investigation. The writer is also indebted to Prof. H. B. Bigelow, director of the Institution. Collection of the samples and nearly all of the laboratory work was conducted while holding a fellowship there. Prof. P. E. Raymond of Harvard University has given generously of his time and counsel.

The first sampling, covering the whole outer beach of the Cape, was made on seven different days during the summer of 1933. The usual interval between stations was approximately one-half mile. On the graphic representation of the results it will be noted that south of Pamet River Coast Guard Station the intervals are larger and more irregular and no low tide samples are shown. In the earlier stages of the investigation, high tide samples were not taken at every station. As will be explained later, not all the low tide samples have been plotted. In 1934 samples were taken, with few exceptions, at high tide at every station. Low tide samples were taken at each station or at alternate ones. Sampling was completed from the northern end of the series to Nauset Coast Guard Station in two days.

MECHANICAL ANALYSIS

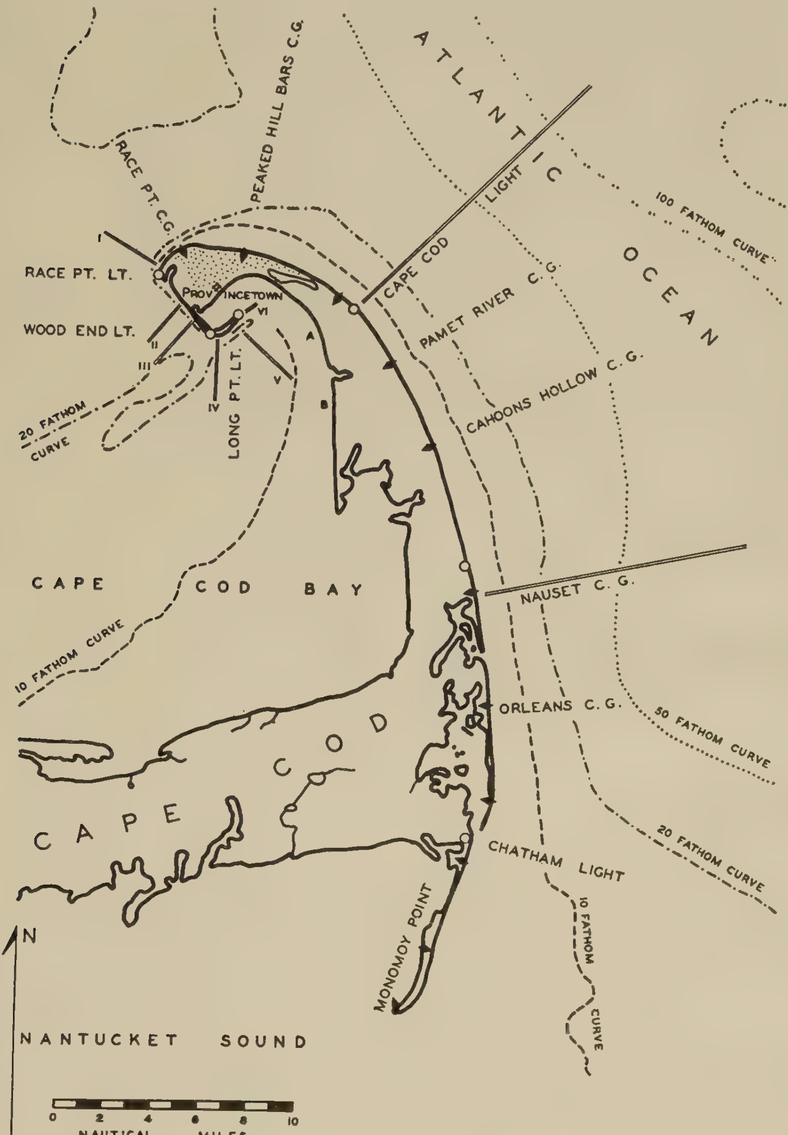
In the laboratory, the samples, weighing from 300 to 400 grams, were washed to remove the salt, and dried. The 40 to 100 grams desired for screening were obtained by hand quartering or by use of a Jones Sampler. The Tyler Standard Screen Series in which the openings of successive screens increase from the 0.074 mm. (200 mesh) in the ratio of the square root of two was used. Separation of the sample into its component sizes was performed on a mechanical shaker which utilized a suspended unbalanced flywheel driven by a quarter horsepower electric motor. After the size fractions had been weighed, the percentages were calculated and cumulative curves constructed. Because of the large number of analyses involved, direct comparison of the curves was obviously impractical. The first quartile, median, and third quartile (i.e., that size which has by weight 75, 50 and 25 per cent of the sample, respectively, smaller than itself) were read from the curves. Comparison of samples is based on the median diameter and the coefficients of sorting and skewness, following Trask (1). Where Q_1 and Q_3 are the quartiles and M the median, the sorting is taken as $\sqrt{Q_1/Q_1}$. Thus "perfect" sorting equals unity; the larger the value the more poorly sorted is the sample. The skewness, an indication of the dis-symmetry of the frequency curve, is derived from the expression $Q_1 \times Q_3/M^2$. For convenience the logarithm of the skewness is used. Thus a minus value indicates that the mode, or peak of the frequency curve is on the coarse side of the median. A positive value indicates the opposite. The median, sorting and skewness have been plotted against distance along the beach in Fig. 2. It must be stressed that no averaging has been attempted in the effort to obtain a smooth "curve." A "running" average would naturally make the curves much smoother, but would give an idealized picture. Also, if one were attempting to apply the findings of the present investigation in a study of an ancient beach, or of its associated near shore deposit, it is very possible that sufficient outcrops or well samples would not be available to allow averaging of the data.

GRAPHICAL REPRESENTATION

Probably the best presentation of the results of this study is contained in Fig. 2. The graphical representation obtained by plotting median diameter and the coefficients of sorting and skewness against distance along the beach gives the essential facts found with far more clarity than is possible in a textual description alone or in combination with lengthy tables. For this reason, the verbal description will be held to a minimum. The ratio of unit of median diameter to unit of distance along the beach may seem large in the graph. It was believed best to spread out the points to separate the high and low tide values of the two different years at the expense of making the "curves" rather irregular. Only a few of the skewness points have been connected.

Median Diameter.—Within the cliff section the 1934 high tide medians vary from slightly more than 0.55 mm. at the northern to less than 0.30 mm. at the southern end. The less numerous 1933 high tide samples likewise decrease to 0.30 mm. toward the south, but, as the graph shows, some of the values near the northern end are above 0.6 mm. The 1934 low tide samples show a southerly decrease from around 0.8 mm. to less than 0.3 mm. The 1933 low tide samples run, for the most part, larger than those taken a year later.

North of the cliff section the 1934 high tide medians increase from 0.55 mm. to 1.3 mm. The low tide medians increase from 0.8 mm. to 1.9 mm. The 1933 sampling roughly parallels that of the following year but with values generally higher.


ATLANTIC
OCEAN
RACE PT. C.G.
PEAKED HILL BARS C.G.
I
RACE PT. LT.
PROVINCETOWN
WOOD END LT.
II
III
IV
V
VI
A
B
LONG PT. LT.
20 FATHOM CURVE
CAPE COD LIGHT
PAMET RIVER C.G.
CAHOONS HOLLOW C.G.
100 FATHOM CURVE
CAPE COD BAY
10 FATHOM CURVE
NAUSET C.G.
ORLEANS C.G.
50 FATHOM CURVE
CAPE COD
20 FATHOM CURVE
CHATHAM LIGHT
MONOMOY POINT
10 FATHOM CURVE
N
NANTUCKET SOUND
0 2 4 6 8 10
NAUTICAL MILES

AFTER U.S.C.& G.S. — CHART 1107

FIG. 1. Location map, Cape Cod.

In the southern section, which has 1933 high tide samples only, the succession is rather irregular. Nevertheless the increase from 0.3 mm. at the southern extent of the cliffs to 0.5 mm. at the end of Monomoy Point, repeats, although to a less striking degree, the condition found in the northern section.

Coefficient of Sorting.—The graph readily shows that the sorting within the cliff or source section is good. The high tide samples are generally the better sorted.

Values range from 1.1 to 1.4. In the northern section the sorting at high tide remains good as far as Race Point. Beyond to Long Point the sorting at low tide becomes very irregular, with several values rising above 1.7 and one reaching 2.74. In the southern section the majority of the sortings are below 1.4. For a short distance near the middle of Monomoy Point they exceed 1.5.

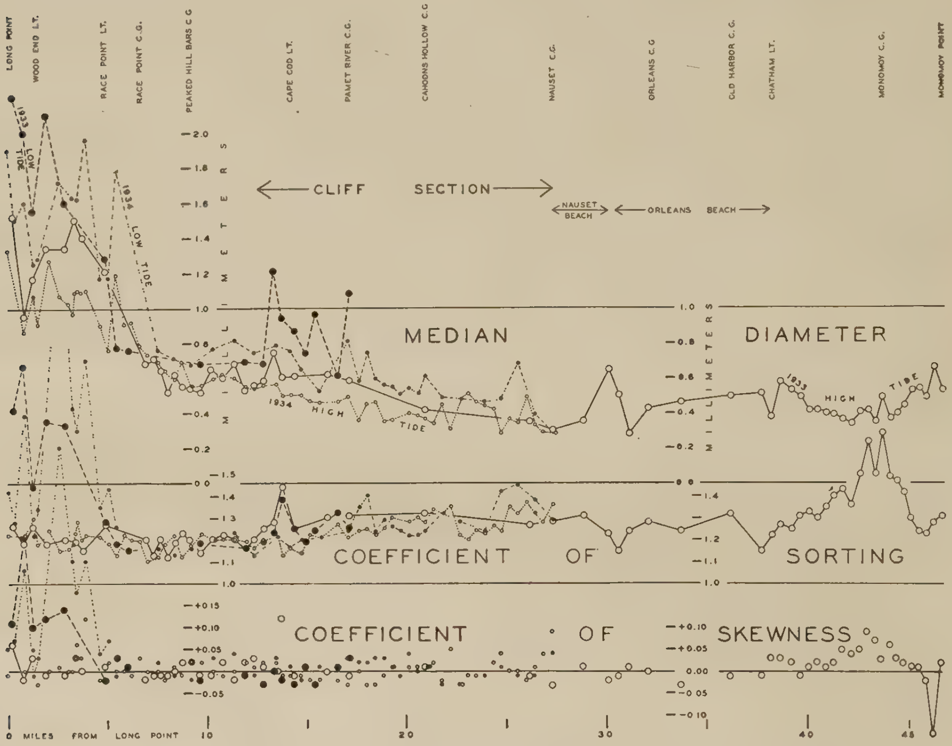


FIG. 2. Graph of the median diameter and coefficients of sorting and skewness.

Coefficient of Skewness.—Examination of the lowermost "curve" in Figure 2 indicates small values for the skewness throughout the central section. Thus, nearly symmetrical frequency curves are indicated with the mode, or peak of the frequency curve, close to the median. The same low values continue for some distance in either direction from the cliffs. Near the end of the northern section where the medians and sortings rise, the low tide skewnesses reach high positive values. Although the sorting remained good in the high tide samples at the end of the series, the skewness values for high tide show considerable positive increase. Here there appears to be a definite tendency for the mode to be on the fine side of the median at both low and high tides. Near the end of Monomoy Point the high tide samples have a similar group of high positive skewness values. However the sorting is also above the average. The significance, of the strong positive skewness is not clear at this time.

The graph shows that the median is smaller, the sorting generally better, the skewness closer to zero at high tide than at low. As the beach increases in coarseness, the spread between the high and low tide medians increases. (On certain very fine-grained beaches sampled by the writer the larger medians were occasionally found at high tide.)

VARIATION AT LOW TIDE

The statistical constants of 56 low or low-mid tide samples taken in 1932 between Pamet River and the south end of Orleans Beach have not been plotted in Fig. 2. Of this number, 32 may be described as samples of a surface layer present at low tide, the remainder as samples of an underlying coarser layer. Where found the surface layer varied from about one-fourth to three-fourths of an inch in thickness; the underlying material continued an indefinite distance downward. In all cases in which both layers were present, the surface layer had the smaller median and the better sorting. Apparent lack of correlation between the two layers is shown by a minimum difference in median of 0.082 mm. and a maximum difference of 2.430 mm. The coefficients of skewness of the surface layer are about equally divided between positive and negative values. The strong tendency towards positive skewness (mode on the fine side of the median) within the lower layer appears due to mixing with the finer sand above.

The samples are of value in that they indicate that a non-uniform cross section may exist on the beach, especially from mid to low tide. The stratification presumably extends out beyond the low tide plunge point. The variability of wave intensity is the logical cause of such stratification. The low tide zone is under continuous wave action at all tides, and the greatest effects should be within that zone. On the upper portion of a beach there is a lesser difference between the intensity and the resultant effect of the swash of a large and of a small wave than there is between the disturbance made by a large wave and by a small wave on the bottom either side of, and at, the plunge point. The uprush following the breaking of a large wave is damped as the water rises to the final swash limit. At the same time, volume is lost by percolation into the sand. The uprush of smaller waves is damped proportionately less because a greater percentage of the wave's travel is over saturated sand. Thus the environment of the upper part of a beach is much more uniform than that of the lower part. It must be added that the swash mark limit moves landward during spring tides and when strong onshore winds pile up the water against the shore. The great difference in intensity between small and large waves at the plunge point is well known to all surf bathers. The higher degree of uniformity of the environment explains the better sorting of the high tide samples.

The stratification at mid to low tide may be explained as follows: A decrease in wave intensity, or seaward movement of the plunge point as the tide ebbs, could leave a layer of the finer sand from the upper portion of the beach, carried down by the backwash, on top of the coarse sand which was in equilibrium when the plunge point stood over or adjacent to it. According to this hypothesis, lack of any stratification would mean an adjustment between wave intensity and the ebbing tide, so that approximately the same amount of energy was expended on the bottom as the plunge point retreated seaward. A lack of marked stratification would also be expected where the sand is extremely fine and well sorted with slight difference between high and low samples.

Lamination in certain California beaches has recently been investigated by Thompson (2). On Cape Cod definite lamination was seen in several places above the then prevailing high tide limit. Difference in grain size between adjoining laminae was very small compared with the difference often found at low tide as described above. It appeared that very small differences in the distribution or content and distribution of the fraction of one per cent of dark minerals present were sufficient to make individual laminae distinguishable from one another in the field.

GEOLOGICAL BACKGROUND

The general geology of Cape Cod has been thoroughly covered in a recent publication by Woodworth and Wigglesworth (3). Its physiographic development has been discussed by many writers, including Admiral Davis (4), W. M. Davis (5), and Johnson (6). For our present purpose we are interested in two factors, the supply of new material available to the beach and the exposure. The latter is a function of the offshore profile and the fetch and intensity of onshore winds. Cape Cod may be divided into three sections; the central, or "cliff" section and the two "end" sections derived from it. The cliff section extends from a point 1.2 miles north of Cape Cod Light south to Nauset Coast Guard Station, a distance of nearly 15 miles. At Orleans Beach, and again at Chatham Light, there are possibilities for additional source material. The low hills at Orleans lie several hundred feet behind the present beach. At Chatham the cliffs beneath the light are now protected by artificial riprap as well as by the underwater extension of the beach to the north. Furthermore, any possible contribution from these sources would be infinitesimal compared with that received from the main cliffs.

The cliffs vary in height from 20 to more than 150 feet, the greater heights being found in the neighborhood of Cape Cod Light. They are entirely unconsolidated and include glacial outwash and clays. The source material thus ranges in size from boulders several feet in diameter to particles of clay dimension. The bulk of the material is in the sand-size grades. Because of the obvious difficulties of taking representative samples of such a heterogeneous mass, no mechanical analyses were attempted. The cliffs retreat at an average rate which long continued observations indicate varies from 3 to 5 feet or more per year, thus placing this material at the disposal of the waves and currents.

Figure 1 shows the very even appearance of the eastern shore line. Within the cliff-backed section there are no inlets. Nauset and Chatham harbors break the continuity of the southern section; Hatches Harbor, a short distance southeast of Race Point, interrupts the northern section. As the cliff front retreats, cutting of the dunes between the northern extent of the glacial deposits and Peaked Hill Bars takes place, thus preserving the even sweep of the arm. Thus the beach receives some dune sand which was originally blown inland from it.

Although there is a slight curve near the end of Monomoy Point, the southern section presents the same straight or gently curved coast line as does the cliff-backed section. The northern section turns very sharply at Race Point and again at Wood End.

Existence of a division point in the long-shore drift is indicated by the general shape of the cape. The dune area known as the Province Lands, plus Race and Long Points north of the cliff section, indicate northerly longshore drift. Conversely Nauset and Orleans and Monomoy Point to the south of the source cliffs indicate southerly drift.

The width of the beach from low tide level to the dune or cliff line is highly variable. In places normal high tide may reach the foot of the cliff talus making travel along the beach very difficult. Elsewhere there is a wide berm (nearly level surface of the sand above normal high tide), or, in places, a lagoon with a ridge rising above normal high tide separating it at one or both ends from the sea. In such instances the distance from dune or cliff base to high tide mark may be 400 to 500 feet.

The slope of the normal inter-tidal zone of the beach is likewise variable. At Long Point the average slope is about 7 degrees. At Race Point slopes as high as 12 degrees have been measured. From there on to Nausett there is a gradual flattening of the beach. In front of Nauset Coast Guard Station the average slope is 2 degrees 45 minutes. Across Nauset Harbor at Orleans slopes are between 8 and 10 degrees. On Monomoy Point the beach has a similarly steep appearance although no measurements were made. The normal tidal range is 9.2 feet at Provincetown, 6.5 at Nauset Harbor, and 3.7 at Monomoy Point.

The slope of the foreshore, which affects both the incoming waves and the size of material which can move seaward over the bottom, varies rather widely off Cape Cod. From Peaked Hill Bars Coast Guard Station south to Nauset the Coast and Geodetic Survey chart shows that the 10 fathom curve is approximately one mile off shore. The 20 fathom curve is from 2 to 2.5 miles off shore.

Off Nauset Harbor the 50 fathom curve is within 5.5 miles off shore. Elsewhere it is much farther, as partly shown in Fig. 1. Southward from Nauset the water shoals so that the 10 fathom curve is 7 miles east of the tip of Monomoy Point. West of Peaked Hill Bars Coast Guard Station the 10 and 20 fathom curves swing towards the shore until the latter curve is less than one-half mile off at Wood End and 600 feet at Long Point. Hence between Nauset and Peaked Hill Bar the foreshore may be characterized as steep, and from Peaked Hill Bar west and south to Long Point, the foreshore is very steep.

Due to the general north-south trend of the outer beach, there is a full easterly exposure from the vicinity of Peaked Bars Coast Guard Station south to Monomoy Point. In addition, southeast and northeast storms reach the beach; waves from the latter direction affect the northern end as far as Race Point. Although it is obvious that a storm from any of these directions will have some effect on this beach, local tradition assigns the greatest violence, and hence fastest cliff retreat, to northeasters.

REPETITION OF SAMPLING

We have seen from Fig. 2 that between Long and Race Points there is an unmistakable parallelism of trend in the median values for 1933 and 1934. This parallelism also exists in the plots for the coefficients of sorting and skewness. In general, the 1934 samples have slightly smaller median values, better sortings and lower skewness values. From Race Point to Nauset there is a closer agreement between the two groups of high tide samples. Just what the agreement and parallelism of trend would be had it been practical to repeat the samplings at intervals throughout the year cannot be stated. The winter preceding the first sampling saw the cliffs retreat in places as much as 30 feet. Thus a huge volume of material ranging in size from boulders and cobbles to clay was received by the beach. During the next winter little or no cliff cutting took place. Yet the analyses for each of the summer samplings, in spite of the immensely different volume of new material, are either very close, or of parallel trend. During a period of cliff cutting, and probably for some time thereafter, the new material must induce some changes in the statistical constants of the beach sand. It is evident, however, that at least with the return of summer conditions, the waves have restored equilibrium.

ORIGIN OF THE WAVE-BUILT SECTIONS

Before undertaking the discussion of the mechanical characteristics of the beach sands, we must consider the origin of the wind and wave-built sections of Cape Cod.

Tidal Currents.—Inasmuch as tidal currents have been used to explain the configuration of Cape Cod, present actual measurements should be considered. In 1849 Admiral C. H. Davis wrote that "There is a split of the tides 6 miles south of Nauset Lights and 9 miles north of Chatham" (in the neighborhood of Orleans). "At this point the flood tide divides, part going north, the rest south." As proof he cites the drift of cargoes of wrecked vessels. North of the division point wreckage has been carried around into Provincetown Harbor. The anchor and chain of a 200-ton brig moved northward on the beach at Truro one and one-half miles in three weeks. Admiral Davis also says, "Nauset Beach advanced two miles between 1829 and 1849, moving the harbor entrance to the south and making an enclosed basin out of what was formerly an open harbor." It is to be noted that this southern advance is north of the supposed tidal division point. Coast and Geodetic Survey measurements[1] of the tidal currents are available at six points off the cape. According to present data there is no place at which the incoming tidal wave divides into north and south components. In other words, on a single tide there is a continuous general sweep from the end of Monomoy Point to the end of Long Point, at Provincetown. More specifically, on the flood tide the general direction between Chatham and Cape Cod Light is N. to N. 45°E. The direction of the ebb is S. to S. 45°W. as the flood sweeps around the curve past Race Point, the direction becomes S. 55°E. off Wood End, reversing to N. 55°W. on the ebb. One mile north, and 1.5 miles off Old Harbor Coast Guard Station, near Chatham, the flood current runs at a knot and a half, the ebb at one-half knot. Two miles off Nauset Harbor the floods runs at one knot, the ebb at one-half knot. One mile off Cape Cod Light, the flood runs at three-fourths of a knot, the ebb at one and one-fourth knots. It is to be noted that the two southerly observations show the higher velocity for the flood tide, whereas the northerly observation has the higher velocity for the ebb. The velocities between Race Point and Wood End, one-half mile off shore, are one and one-fourth, one and one-fourth, and one-half knots, respectively, the last observation being off Wood End.

W. M. Davis and Johnson in their account of the growth of Cape Cod both give Admiral Davis' article as a reference; the former author quotes directly from the admiral's section on the north-south tidal division point. Hence the belief has continued that tidal currents are responsible in no small measure for the present configuration of Cape Cod.

The evidence from recent measurements of the tides may be summed up as follows: 1) There is no division point which would result in northward and southward flowing currents generated by a single tide. 2) Off Nauset Harbor, where the direction of growth of Nauset and Orleans Beaches indicates that longshore drift is to the south, the flood or northward flowing tide has the greater velocity. Off Cape Cod Light, where the Provincelands indicate a northward longshore drift, the ebb tide has the greater velocity. We may, therefore, conclude that any difference in the flood and ebb velocities cannot be the cause of the southerly drift south of Nauset Coast Guard Station nor of the northerly drift prevailing north of Cape Cod Light.

Influence of the Waves.—The facts nevertheless demand a division point somewhere within the cliff section. This point must shift a not inconsiderable distance with every shift in storm direction and resultant change in the angle at which the waves strike the beach. At Race Point Coast Guard Station sand and driftwood have been observed by the author travelling to the westward under the influence of large northeast storm waves. Farther south the waves generated by the same storm had a southward component and the swash was transporting the surface material in that direction. Evidence would thus point to control by the angle of incidence of the most effective waves.

Volumes Involves.—Although the physiographic evidence of the drift directions is very clear, the following considerations of the volume of material involved is of interest. What has been referred to as the southern section of the cape begins at Nauset Coast Guard Station at the southern limit of the cliffs. Nauset Beach, attached to the mainland at this point

---

[1] Personal communication from the Director, August 13, 1935.

(see fig. 1), extends to the south for about 3 miles. The area of this wave built form is approximately 0.45 square miles.[2] Orleans Beach springs from the slightly higher land across Nauset Harbor and extends to the south towards Chatham. Its length is about 7 miles and its area is more than 1 square mile. Monomoy Point extends in a southerly direction from Chatham for approximately 8 miles. At times the point has been severed from the mainland for long periods. More recently, only occasional storms have broken through the beach and these are soon closed by longshore drifting. The area of the point exceeds 2.2 square miles. Between 1853 and 1868 the southern end of the point increased in area by approximately 450,000 square yards (7), or at the rate of 30,000 square yards per year. Comparison of the 1868 chart with one of 1925 indicates a further increase of 643,000 square yards or accretion at a rate slightly exceeding 11,000 square yards a year. If the extensions were built in water 12 feet deep and to a height of 3 feet above tide the volume involved is tremendous—55,000 cubic yards per year between 1868 and 1925. As each 3 foot retreat of the cliff section south of Pamet River yields in the neighborhood of 336,000 cubic yards, it is evident that there is ample material coarse enough to remain on the beach during transport. Consideration of this huge volume of material moved to the southward leaves no possible doubt as to the effective direction of longshore drift in the area.

At the same time, the evidence for a northwesterly drift from the northern end of the cliffs north of Cape Cod Light is extremely well founded. The dune covered area of the Provincelands to the west and north of the cliff section (dotted area in figure 1) is in excess of 6 square miles. About 2 square miles have dunes which exceed 60 feet in height. Between Race Point and Wood End the drift direction has swung into the southeast. At Wood End it turns again so that Long Point is advancing in a northeasterly direction. Between 1835 and 1867 Long Point advanced 2,460 feet (8). The rate of advance has apparently become more irregular and has decreased considerably since comparison of a chart of 1890 with one of 1935 shows no very great change in the position of the end of the point. (The scale of the charts is 1–80,000.) However, Shepard (9) reports that between 1921 and 1931 the point advanced at the rate of 52 feet per year, considerably less than the 77 feet per year between 1835 and 1867. As in the case of the southern extension, the volume of wave and subsequently wind transported material abundantly proves that the effective drift direction north of Cape Cod Light is away from the cliff section.

SIGNIFICANCE OF THE MEDIAN CURVE IN THE GROWTH OF THE BEACH

With the cliffs the recognized source of the beach material, it is now necessary to explain the occurrence of the smaller medians within this section. As we have seen, the larger medians occur to the north and south in the wave and current built sections which project in the direction of longshore drift prevailing in that area. The coarsening in the direction of drift differs from the relationship found by Pettijohn (10) and by MacCarthy (11). Both of these authors noted a decrease in median in the direction of drift.

Mechanical analyses of samples taken between Charleston, S. C., and Miami, Fla., by Martens (12) gave an increase in median from about 0.2 mm. at Charleston and Jacksonville to about 0.4 mm. at Miami. Although the increase is in the direction of longshore drift, the wider spacing of the samples, the high percentage of calcareous sand, and the lack of a well-defined source comparable to the Cape Cod cliffs, prevent an effective comparison.

---

[2] This, and the succeeding areas and volumes given are estimated from the Wellfleet, Yarmouth and Provincetown sheets, U. S. Geol. Survey, and from U. S. Coast and Geodetic Survey charts. Accurate planimeter measurements were not attempted.

Various hypotheses were considered as possible explanations of the anomalous median diameter curve. Perhaps the first and most obvious explanation would be in the exposure. Examination of Fig. 1 shows that the zone of smaller medians, the cliff section, has a full eastern exposure. Contrasted with this situation is the tip of Long Point where are found the coarsest medians. Long Point is subjected only to waves generated within the limits of Cape Cod Bay. South of Race Point to Long Point the greatest fetch is not over 36 miles. In this respect, two samples taken on the shore of Cape Cod Bay at points marked *A* and *B* in Fig. 1 are of interest. Their medians, 0.64 and 0.52 mm., respectively, compare with values of approximately 0.50 mm. found directly to the east on the ocean side of the cape. The westerly storms are not comparable with the northeasters which attack the cliff section. Local residents state that a year without a strong northeaster means little or no change in the cliffs. One big storm, when it does come, may cause a retreat of 10 to 20 feet or more.

The relative steepness of the foreshore is admittedly a factor of exposure as well as the available fetch. Figure 1 shows that the steepest foreshore is present in the vicinity of Race Point and on to Wood End and Long Point. South of the vicinity of Orleans Coast Guard Station, the foreshore shoals rather rapidly. Yet, as the plot shows, the medians increase on Monomoy Point. Moreover the shallow foreshore here does not prevent the waves from occasionally cutting through the beach south of Chatham and making Monomoy temporarily an island. Further evidence that steepness of foreshore is not the controlling factor in the Race Point-Long Point stretch is offered by the bottom samples discussed below.

Tidal directions and velocities have already been ruled out as possible explanations.

Progressive Loss of Fines.—After consideration of the above and of several other possibilities, it appeared that progressive loss of the finest remaining grades of sand during longshore drift was the answer. Various lines of evidence combine to support this hypothesis. They will be discussed in turn.

Evidence from the Smallest Grade Size.—A comparison of the smallest grade size (present to amount of 0.1 per cent or more) gives an interesting picture. It is perhaps more graphic than the median curve as it necessarily indicates slighter changes than are reflected in the median. The figures show that on Long Point there is nothing smaller than 0.589 mm. As we proceed along the beach towards Race Point the percentages shift into the next smaller grade sizes so that at Race Point the finest sand is in the 0.417 and 0.295 mm. grades. At Peaked Hill Bar the first appreciable percentage, 0.1 per cent appears in the 0.147 mm. size. The first sample with 0.1 per cent of 0.104 mm. grade is at Cape Cod Light. South of Cahoons Hollow the percentages in the 0.104 mm. grade increase, reaching a maximum of 1.1 per cent at Nauset Coast Guard Station. On Orleans Beach one sample runs as high as 0.7 per cent in the 0.104 mm. grade. On Monomoy there is for a short distance an increase in the 0.104 mm. grade, but values do not exceed 0.1 per cent. At the end of Monomoy Point the next larger size, 0.147 mm., has dropped to 0.1 per cent. Clearly, then, the finer sizes are more abundant on the southern wave built extensions than on the northern, and are present in greatest abundance beneath the southern portion of the cliffs.

Bottom Samples.—As previously stated, six short lines of bottom samples were taken off the beach in the Race Point-Long Point section by the Oceanographic Institution. Each line was begun as close to the beach as it was practical to bring the 40 foot boat used for dredging. Stations were generally spaced at one-eighth to one-quarter mile intervals. On the first line, off Race Point, the median decreases from 0.65 mm. (depth of 4 meters) to 0.30 mm. (60 meters) for the seventh station, 1 mile off shore. Intermediate medians are 0.55, 0.57, 0.61, 0.56 and 0.47 mm. On the second line, which runs off shore normal to the beach about half way between Race Point and Wood End, the decrease is from 0.83 mm. (6 meters) to 0.21 mm. (depth of 55 meters). Intermediate medians are 0.80, 0.97, 0.18 and 0.24. The depths at the third and fourth stations, between which a great decrease takes place, were 40 and 54 meters respectively. Lines III to VI are similar to Line II and need not be given in detail. Thus on Lines II to VI there is no gradual decrease between the inshore medians which range between 0.6 and 1.0 mm. and more, and the deeper samples with medians of 0.2 mm. or less. The abrupt change in median values coincides with the contact between the sand of the wave-built portion and the original bottom material of the area. The failure to find a gradually decreasing median curve between the beach and the base on which it is built can only mean that material less than 0.5 mm. in diameter is not advancing in any quantity from the beach southeast of Race Point to deeper water. Actually some fine sand is present; quantitatively it is unimportant, as is shown by the good sortings. It follows, therefore, that the larger part of the sand below 0.5 mm. in diameter leaves the beach between the cliff section and Race Point. The presence of an appreciable percentage of 0.417 mm. grade on Race Point and its absence on Long Point indicates that the smaller waves of Cape Cod and Massachusetts Bays are able to remove this size to deeper water. Hence these smaller waves would readily remove finer sizes if they had not already been lost to the beach by the time Race Point is reached.

Two groups of bottom samples taken on lines normal to the beach off the cliff section indicate that the finer sand is moving off shore here. The line off Cape Cod Light has median values ranging from 1.5 to 0.255 mm. Nine miles off shore at a depth of 145 meters the median was 0.360 mm. The line off Nauset Light has values between 1.46 and 0.114 mm., the latter value being the median at a depth of 135 meters, 7.2 miles from shore. This decreasing median gradient indicates that material of much wider size range, compared with that of the Race Point-Long Point section, is in transit to deeper water. From the evidence of the size grades present on the beach and on the bottom off shore, we may conclude that the larger proportion of the grains below 0.5 mm. in diameter is lost to the beach either in the cliff section or before longshore drift brings the material past Race Point. The size indicated applies strictly to the zone of northward drift. In the Nauset-Monomoy section much finer size grades, even the 0.104 mm., are present in limited quantity on the beach.

Volume of Cliff Feed.—Further evidence on the seaward migration of the finer particles is afforded by consideration of the volume of material of all sizes released by retreat of the cliffs. A simple estimate of the volume of each 3-foot retreat of the cliff front between Pamet River (a conservative choice of division point between north and south drift) and the northern limit of the cliffs, gives a prism approximately 150 × 30 × 50 yards. If a 45-year period is considered with an average retreat of 3 feet instead of the 3.2 feet calculated by Marinden (13) and three-fourths of the cliff material were to reach Long Point, assuming a spit 150 yards wide, building out into water 29 yards deep to a height of 1 yard above tide, the end of the point should advance 1688 yards or nearly one mile. Since comparison of U. S. Coast and Geodetic Survey charts of 1890 and 1935 indicates that no such advance has taken place in the last 45 years, it is obvious that only a very small proportion of the cliff material ever reaches Long Point. This, we see, is the coarser fraction. The remainder, which is the finer fraction, must be carried to sea.

Proof of the generally assumed difference between the on and offshore wave velocities which selectively removes the finer material has been established by the Beach Erosion Board (14). Observations with instantaneously reversing current meters indicate that the onshore velocity is greater in nearly all cases than the offshore velocity, although the onshore motion is of shorter duration.

Examination of the location map, Figure 1, shows a similarity between the Race Point-Wood End stretch of beach and that extending for about 2 miles from the northern extent of the cliffs towards Peaked Hill Bar Coast Guard Station. Each is a rather narrow beach, backed by a marsh, and each connects to leeward of the drift direction with a larger land mass; in the first case, Long Point, and in the second, the Provincelands. Both serve, therefore, merely as "supply pipes" to transfer the drift material farther from its origin. Although it is possible that a great storm might break through the beach into the marsh beyond, any breaches will soon be filled in as long as there is a supply of new material from the cliffs.

Effect of the Wind.—The beach between the vicinity of Peaked Hill Bar and Race Point Coast Stations is the only apparent source of the fine sand in the dunes of the Provincelands. As previously stated, the volume of the dunes is enormous, there being 2 square miles in which they rise to heights exceeding 60 feet. The total area is more than 6 square miles. Thus we see that the wind, by blowing fine sand inland is in part responsible for the increase in the median on the beach between the northern end of the cliffs and Race Point. However, we have seen that the increase in median diameter continues from Race Point on to Wood End and Long Point. As conditions here do not parallel those bordering directly on the Provincelands, it appears that the wind is not sufficient explanation of the great decrease in median diameter.

A glacial deposit which has been reported from Wood End might be considered by some as the source of the coarser material in that section. Woodworth (3) mentions a "zone of angular pebbles" which Vaughan is supposed to have noticed at low tide on the beach at Wood End. Three careful searches, in Three careful searches, in three successive summers, have failed to reveal the supposed glacial deposit. However, rounded cobbles up to 6 inches in diameter are present in the extreme low tide zone. If the angular pebble deposit actually existed, it presumably formed only a small portion of the otherwise wave- and wind-built form. Such a deposit could not in itself explain the increase in median diameter between Wood End and Long Point.

Movement of the Coarsest Material.—As stated in the preceding paragraph, there are cobbles up to 6 inches in diameter in the low tide zone of the Wood End-Long Point beach. In the talus at the base of certain sections of the cliffs material of similar size is also visible. On the intervening beach, at least above low water level, no cobbles are visible. Transportation from the source cliffs must take place in the zone of the low tide plunge point. The relatively small waves of Vineyard Sound and Buzzards Bay near Woods Hole are sufficient to move cobbles of equal or greater size. Pathways to deeper water on bathing beaches cleared of such cobbles may become obliterated by the same ones moving back many times during the course of a single summer. It is also probable that some of the coarsest material is concealed under the berm, where one is present, and is subjected to longshore movement only during storms accompanied by excessively high water. At one point on the Marthas Vineyard Beach between Gay Head and Squibnocket Point artificial draining of a pond had cut a channel across the beach. Beneath the fine-grained berm a pavement of 3 to 4 inch cobbles was revealed. As long as there is sufficient supply of fine-grained sand available, the pebble and cobble sizes generally seem to be concealed. On Long Point the absence of practically all grains below 0.5 mm. in diameter "uncovers" the coarsest sizes which have nevertheless been transported from the same source. On Cape Poge Spit, Chappaquiddick Island, directly to the east of Marthas Vineyard, much the same situation exists on a smaller scale. Close to the cliffs the coarser size elements travel along below low tide, or remain beneath the berm between major storms. As the finer sand is lost from the beach, the coarser material appears higher and higher, until at the end of the spit there are no particles at high tide less than 0.417 mm. in diameter. Beneath the source cliff 88.2 per cent of the sand is smaller than 0.417 mm. The high tide medians on this two mile spit, beginning beneath the small source cliff, are 0.242, 0.570, 0.490, 1.14, 2.32 and 1.28 mm. On the basis of the foregoing evidence, longshore transportation of the coarsest particles found is not a problem impossible of explanation.

SUMMARY

The mechanical analyses of sands from the outer beach of Cape Cod between Long Point at Provincetown, and Monomoy Point, south of Chatham, may be characterized as follows:

In the cliff, or source section, the medians at high tide vary from about 0.55 mm. at the northern limit, 1.2 miles north of Cape Cod Light, to less than 0.30 mm. at Nauset Coast Guard Station, the southern limit. In approximately the same distance, the median at low tide decreases from about 0.80 mm. to less than 0.30 mm.

In the northern section the median increases from about 0.55 at the northern end of the cliffs to 1.30 mm. at the end of Long Point. Over the same distance the low tide medians increase from about 0.80 to 1.90 mm.

In the southern section the median increases from 0.30 mm. at Nauset to more than 0.50 mm. at the end of Monomoy Point.

The small values of the coefficient of sorting prevailing at high tide (less than 1.4 except for a short distance on Monomoy Point) indicate good sorting here. The sorting at low tide is much more variable with generally poorer sorting among the coarsest samples at the northern end of the series.

Low values for the coefficient of skewness are found everywhere except in the samples, both high and low tide, at the northern end, and in a small group on Monomoy Point. The exceptions uniformly show a strong tendency for the mode to be displaced on the fine side of the median.

There is thus an increase in median diameter in the direction of the longshore drift which has transported the huge volume of material now forming the northern and southern sections of the cape. The possibility of a control of the drift by tides is negatived by existing measurements of their direction and velocity. There is no point at which the tide produces currents which divide into northward and southward flowing components; and the greater tidal velocities run contrary to the direction of advance of the wave built forms. Thus the older theories which base the configuration of the cape in tidal control are not compatible with present knowledge. From the evidence now available it appears clear that the longshore drift is controlled by the angle of incidence of the major storm waves.

After consideration of several possibilities it appears that the beach beneath the cliff section has smaller medians because of the proximity of the supply. As emphasized, the supply is heterogeneous and consists of boulders, cobbles, gravel, sand and clay. The finer grades are lost to deeper water during longshore transport rapidly enough to result in an assemblage of the surviving coarser grains on Long Point, and a somewhat less coarse-grained assemblage on Monomoy Point. Long Point has advanced into water between 15 and 20 fathoms deep;

Monomoy into water less than 10 and perhaps less than 5 fathoms deep.

Off Nauset Light, Cape Cod Light, and Race Point, lines of bottom samples give support to the view that considerable sand of all sizes is moving seaward over the bottom. In contrast, lines off the Race Point-Long Point beach show a sudden decrease from coarse (0.60 to 1.00 mm. median) material to silt (median of about 0.20 mm.). The silt appears to be the natural bottom material over which the wave built section has advanced. Therefore we infer that most of the sand less than 0.50 mm. in diameter is removed from the beach before the remainder arrives at Race Point.

The ability of the sea to restore equilibrium is shown by the similarity between the 1933 and the 1934 station values. In the winter preceding the first sampling the cliffs suffered a retreat of as much as 30 feet in many places. Despite the huge volume of fine material received, the waves removed practically all particles below a diameter of 0.104 mm. During the ensuing winter there was a minimum of cliff cutting, yet the following summer the median gradient closely paralleled that of the preceding summer. It is evident, therefore, that the waves restore equilibrium within a short time.

In one sense a beach similar to that of Cape Cod is extremely temporary; an individual grain of sand probably does not remain in one place for any great length of time. But when it moves away, its place is taken by another of similar characteristics so that the sand community remains essentially the same. Thus a mechanical study of the beach at any one time tends to give an explanation of the type of material being removed from the beach and an explanation of the sediment which it is forming. Of course this cannot hold true for a "pocket" or enclosed beach without a continuing source of supply. Such a beach cannot be a source for any appreciable sediment off shore.

From the study of this modern beach it follows that under similar conditions, an ancient beach may have a median diameter gradient which increases in the direction of the drift which was responsible for its formation. The same would necessarily hold true for the associated near shore sand deposit which might alone remain preserved in the sedimentary column.

REFERENCES

(1) Trask, P. D., *Origin and environment of source sediments of petroleum*, Houston (1932), 67–76.

(2) Thompson, W. O., Original structures of beaches, bars and dunes: *Geol. Soc. Am., Bull.*, 48 (1937), 723–752.

(3) Woodworth, J. B., and Wigglesworth, E., The geology of Cape Cod and the New England Islands: *Mus. Comp. Zoology, Mem.*, vol. LII (1934).

(4) Davis, (Admiral) C. H., A memoir on the geological action of tidal and other currents: *Am. Acad. Arts and Sci., Mem.*, N.S. 4, pt. 1, (1849), p. 122.

(5) Davis, W. M., The outline of Cape Cod: *Am. Acad. Arts and Sci., Proc.*, 41 (1896), 303–332.

(6) Johnson, D. W., *New England-Acadian shoreline*, New York (1925).

(7) Mitchell, H., U. S. Coast Survey Rept. for 1871 (1874), 134–143.

(8) Whiting, H. L., U. S. Coast Survey, Ann. Rept. for 1867.

(9) Trowbridge, A. C., and Shepard, F. P., Sedimentation in Massachusetts Bay: *Jour. Sedimentary Petrology*, 2 (1932), 24.

(10) Pettijohn, F. G., and Ridge, J. D., A textural variation series of beach sands from Cedar Point, Ohio: *Jour. Sedimentary Petrology*, 2 (1932), 76–88.

(11) MacCarthy, G. R., Coastal sands of the eastern United States: *Am. Jour. Sci.*, 22 (1931), 35–50.

(12) Martens, J. H. C., Beach sands between Charleston, S. C., and Miami, Fla.: *Geol. Soc. Am., Bull.*, 46 (1935), 1563-1569.

(13) Marinden, H. L., U. S. Coast and Geodetic Survey, Rept. of Supt. for 1889, Appendix 12 (1890), 403-407.

(14) Interim Report of Beach Erosion Board, Office of Chief of Engineers, U. S. Army, Washington, April 15, 1933, paragraphs 3/35 and 3/36.

Contribution No. 147

5.

Plankton of the Bermuda Oceanographic Expeditions. VIII. Medusae Taken During the Years 1929 and 1930[1].

HENRY B. BIGELOW
Museum of Comparative Zoology, Harvard College.

(Text-figs. 1-23).

[This is one of a number of papers dealing with the planktonic contents of nets drawn at various levels off the coast of Bermuda on the Bermuda Oceanographic Expeditions of the New York Zoological Society under the direction of Dr. William Beebe. Full details of the nets, locality, etc., will be found in *Zoologica,* Volume XIII, Numbers 1, 2 and 3, and Volume XXI, Numbers 3 and 4.]

CONTENTS.

PAGE
INTRODUCTION 101
  ANTHOMEDUSAE 102
    Zancleopsis 102
      Zancleopsis dichotoma Mayer 102
    Bougainvillia 104
      Bougainvillia niobe Mayer 104
    Pandea 106
      Pandea conica Quoy and Gaimard.....106
      Pandea rubra Bigelow 107
    Heterotiara 108
      Heterotiara anonyma Maas 108
    Calycopsis 108
      Calycopsis sp ? 108
  LEPTOMEDUSAE 109
    Chromatonema 109
      Chromatonema rubrum Fewkes 109
    Aequorea 110
      Aequorea floridana L. Agassiz.....111
  TRACHOMEDUSAE 112
    Olindias 112
      Olindias phosphorica tenuis Fewkes 113

---

[1] Contribution No. 554, Department of Tropical Research, New York Zoological Society.
Contribution No. 147 of the Woods Hole Oceanographic Institution.
Contribution from the Bermuda Biological Station for Research, Inc.

PAGE
Rhopalonema 113
Rhopalonema velatum Gegenbaur 113
Pantachogon 114
Pantachogon haeckeli Maas 115
Colobonema 116
Colobonema typicum Maas 117
Crossota 118
? *Crossota brunnea* Vanhöffen....119
Trachynemidae genus ? 120
Halicreas 120
Halicreas minimum Fewkes 122
? *Halicreas glabrum* Vanhöffen 124
Halitrephes 125
Halitrephes valdiviae Vanhöffen 125
Liriope 126
Liriope tetraphylla Chamisso and Eysenhardt....127
Geryonia 127
Geryonia proboscidalis Forskål 127
NARCOMEDUSAE 128
Cunina 128
Cunina sp? 128
Solmissus 129
? *Solmissus incisa* Fewkes 129
Aegina 130
Aegina citrea Eschscholtz 131
Aeginura 132
Aeginura grimaldii Maas 132
Pegantha 134
? *Pegantha clara* R. P. Bigelow....134
SCYPHOMEDUSAE 135
Carybdeida 135
Carybdea 136
Carybdea marsupialis xaymacana Conant....139
Carybdea alata Reynaud 144
Tamoya 150
Tamoya haplonema Müller 151
Periphylla 155
Periphylla hyacinthina Steenstrup 155
Nausithoe 159
Nausithoe punctata Kölliker 159
Atolla 160
Atolla wyvillei Haeckel 160
Linuche 163
Linuche unguiculata Schwartz....163

PAGE
DISCOPHORA 164
Pelagia 164
Pelagia noctiluca Forskål 164
Poralia 165
? *Poralia rufescens* Vanhöffen 165
Aurellia 167
Aurellia aurita Linné 168
FAUNISTIC CONSIDERATIONS 169
VERTICAL DISTRIBUTION OF MEDUSAE AS A WHOLE....................170
RELATIVE ABUNDANCE OF DIFFERENT SPECIES........................172
ABSOLUTE ABUNDANCE 172
QUANTITATIVE COMPARISON WITH OTHER REGIONS......................172
BIBLIOGRAPHY 174
APPENDIX 180

INTRODUCTION.

The medusae recorded in the following pages were taken by Dr. William Beebe within a roughly circular area, some eight miles in diameter, centering about 9 miles about south-southeast from the eastern end of the Bermuda archipelago. Within the area of study, the depth ranges from 1,357 to somewhat less than 1,500 fathoms.

Horizontal towing with open nets was carried out in each year at frequent intervals from April through September, at various levels from the surface down to 2,195-0 meters, the total number of tows being 528 for 1929, 488 for 1930. An account of methods of collection, with list of tows, has been given by Beebe (1931). In this list, the depths stated are those at which the horizontal parts of the tows were made, determined—at least in some cases—by a recording pressure-gauge or "Bathygraph" (Beebe, 1931, p. 13, Fig. 6). But one must remember that as the nets used were of the ordinary open type, which fish nearly as effectively while being lowered as while being towed horizontally, and as effectively while being hauled up again, there is no way of determining from what depth any particular specimen may have come. The depths of the hauls, given under the several species in the following pages, are therefore stated accordingly. However, so many hauls were made on each towing day, and at so many different levels, that differential results show fairly well the upper limits of occurrence; also the chief levels of abundance for the more common species. But none of the species was taken in numbers large enough to allow calculation of the probable degree to which the catches were contaminated by specimens picked up during the vertical parts of the tows (for further discussion of this subject see Bigelow and Sears, 1937, p. 69).

The collection contains no new species. But it adds to morphological knowledge of several. And it is especially interesting from the distributional standpoint, being the only intensive and long-continued campaign of deep towing that has yet been made at one place in the open ocean. With so many hauls, made at such close intervals, it is unlikely that any medusa was missed that was at all common, or that occurred other than sporadically. It is therefore safe to assume that the catches listed below give a representative picture of all the species of medusae that occurred with any regularity between the surface and the bottom of the sea, at the chosen station, during the summers of 1929 and 1930, except *Cyanea,* which as Dr. Beebe informs me, was occasionally seen at the surface.

ANTHOMEDUSAE.

CLADONEMIDAE.

Zancleopsis.

This genus was proposed by Hartlaub (1907, p. 116) for a bitentaculate medusa from the Tortugas, described by Mayer (1900) as *Gemmaria dichotoma,* but which differs from typical *Gemmaria* (the latter is probably a synonym of *Zanclea*) in the fact that its tentacles are branched, with the branches as well as the main trunk terminating in swollen bulbs; structures very different from the stalked nematocyst knobs with which the tentacles of *Gemmaria* (or *Zanclea*) are armed. *Zancleopsis* also possesses ocelli, which are lacking in *Gemmaria.* And the new genus was accepted by Mayer (1910) in his subsequent monograph.

Zancleopsis was not reported again until 1928 when Kramp (1928, p. 40) described a second species—*tentaculata*—from a single specimen from the Pacific. The Bermuda series now yields a third record of the genus.

Mayer's specimens from the Tortugas had only two developed tentacles. But it appears that they were juveniles, for while he stated that the gonads are developed on the inter-radial sides of the manubrium, his illustrations give no indication that the sex tissue had actually appeared, which accords with the small size of the specimens (3 mm. high), contrasted with the Bermudian example (20 mm. high). Therefore, it is entirely possible that the bulbs alternating with the formed tentacles of Mayer's specimens would later have developed filaments, thus raising the tentacle number to four. And this is made the more likely by the fact that Kramp's Pacific specimen (4.5 mm. high) showed just this state, i. e., one pair of large branched tentacles and one pair of much smaller simple tentacles. It also showed a more advanced stage in the sexual development, with the gonads forming "a number of vertical folds, four on each of the inter radial sides of the stomach" (Kramp, 1928, p. 41). The Bermuda example illustrates a stage still more advanced, the sex folds being more numerous (p. 104), the secondary tentacles about as long as the primary, though still continuing simple, and the size much greater. In short, it seems altogether probable that we have to do here with the final stage in growth of Mayer's juvenile *Z. dichotoma,* a conclusion favored by the fact that there is no faunistic discontinuity, so far as medusae are concerned, between Bermuda and southern Florida.

But it appears that the Pacific *Z. tentaculata* is distinct, for not only does it have large gonads at a much smaller size, but the tentacular spurs, bearing the ocelli, are not so highly developed, and the edges of its radial canals are pictured by Kramp as smooth, whereas they are jagged in the Bermuda specimen.

Zancleopsis dichotoma Mayer.

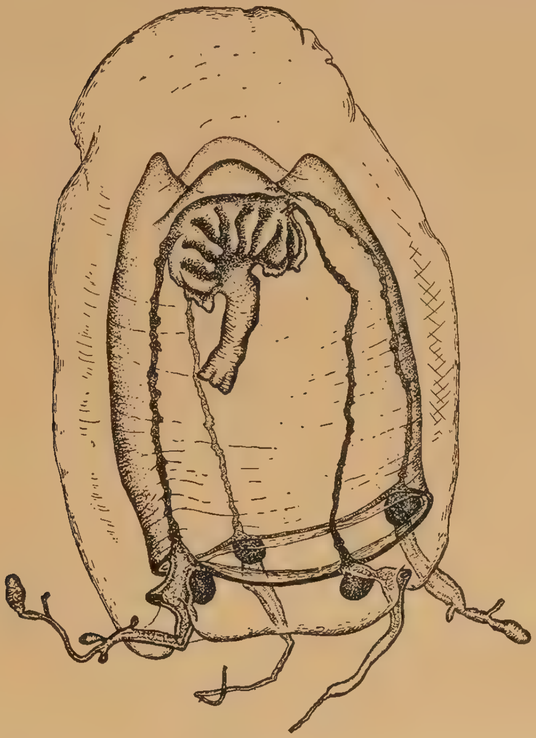
Gemmaria dichotoma, Mayer, 1900, p. 35, Pl. 17, Fig. 40.

Zancleopsis dichotoma, Hartlaub, 1907, p. 115; Kramp, 1928, p. 42.

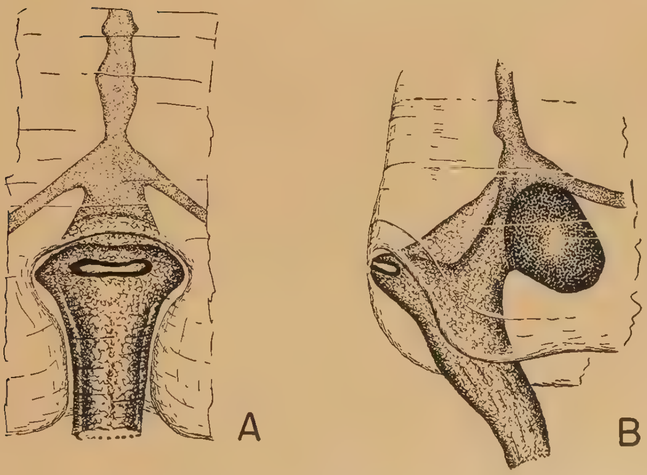
Material: Net No. 922, 1,097-0 meters, September 20, 1930, 1 specimen, 20 mm. high by 14 mm. broad, in good condition.

As the adult has not been seen previously, an account of the significant features follows:

The bell is high domed, moderately thick walled, especially apically (Text-fig. 1), resembling Kramp's (1928, Fig. 14) picture of the Pacific *tentaculata* in general form, except that the apex is rounded instead of pointed. And this minor difference may be merely the result of the preservative. The exumbrella is smooth as Hartlaub has also noted, without any



Text-fig. 1.
Zancleopsis dichotoma. Bermudian specimen, 20 mm. high.



Text-fig. 2.
Zancleopsis dichotoma. Tentacular bulb. **A.**, Abaxial view; **B.**, Lateral view. x about 12.

trace of the nematocyst-ribs so conspicuous in *Zanclea*. The subumbrella occupies about ⅔ the heighth of the bell, with the bell-cavity projecting, pouch-like, apically, in the interradii, in form easier pictured (Text-fig. 1) than described; again much as Kramp figured it for the Pacific species. The four radial canals are of moderate breadth, their margins distinctly jagged (smooth in *tentaculata*). The margins of the circular canal are smooth.

The four subspherical tentacular bulbs, about equal in size, are prominent axially. Just distal to its bulb, the tentacle base is also expanded, abaxially, as a spur (Text-fig. 2) lying in a furrow of the exumbrella, and with a curious cap-like mass of large, clear cells (apparently ectoderm) on its outer (abaxial) side. On its outer angle the spur bears a prominent, long oval ocellus (Text-fig. 2A). The four tentacular filaments are all of about the same length—in the preserved state about ⅓ as long as the bell is high. One pair are simple, the other pair branched. Of the latter, one bears a branch out near the tip, two sessile knobs about mid-way the length of the filament (distal to which the latter narrows abruptly), besides a swelling apparently the forerunner of an additional branch. The other tentacle of this pair bears two small branches, but is so strongly contracted that it is impossible to tell how extensible the latter may have been. The two branched primary tentacles terminate in large knobs. The two secondary tentacles do not, but their tips are in poor condition.

The area of connection between the base of the manubrium and the subumbrella is cruciform, much as described by Kramp for *tentaculata;* its upper ⅓ is thrown into a very characteristic series of vertical folds. These are no doubt the sites of the sexual tissue, as interpreted by Kramp, but eggs not being visible (i.e., the specimen apparently being a male), this point could not be determined positively without microscopic sectioning. In the Pacific specimen of *tentaculata,* there were 3-4 such folds in each interradial sector of the manubrium (Kramp, 1928, p. 41, Fig. 15). In the present specimen the number is greater, 4-6 per interradius, precise enumeration depending on what does, or does not, deserve the name "fold." Below the level of attachment of the radial canals the folds apparently form a continuous series surrounding the manubrium, but as Kramp points out, sectioning would be required to show to what extent the masses of sex tissue are confluent. In the preserved state, the distal tube-like portion of the manubrium hangs to about the mid-level of the bell cavity. But as it is much wrinkled, it is probably contracted, hence may have been considerably longer in life.

After preservation with formalin, manubrium and tentacular bulbs are of an opaque, dull brownish hue; the pigment ring of each ocellus, dull red.

A comparison of Text-fig. 1 with Kramp's (1928, Figs. 14-18) illustrations of *Z. tentaculata* will sufficiently emphasize the close resemblance between the two, especially as regards the structure of the tentacles. The chief differences—probably sufficient to separate two species—are summarized above (p. 102). Minor differences in the outline of the bell and the shape of the manubrium are probably to be credited to the preservative.

BOUGAINVILLIIDAE.

Bougainvillia.

Bougainvillia niobe Mayer.

Bougainvillia niobe, Mayer, 1894, p. 236, Pl. 1, Fig. 2; 1900, p. 42; 1904, p. 11, Pl. 2, Figs. 14-15c; 1910, p. 166, Pl. 18, Figs. 1-3; Bigelow, 1918, p. 368.

Material: Surface, July 11, 1929, 1 specimen, 9 mm. diameter, with medusa buds.

Net No. 562, 914-0 meters, May 10, 1930, 1 specimen, 9 mm. diameter, with medusa buds.

Net No. 738, 1,463-0 meters, June 28, 1930, 1 specimen, 9 mm. diameter, with gonads.

Net No. 812, 1,463-0 meters, August 28, 1930, 1 specimen, 10 mm. diameter, with gonads.

Net No. 862, 1,463-0 meters, September 8, 1930, 1 specimen, 10 mm. diameter, with gonads.

Net No. 915, 549-0 meters, September 19, 1930, 1 specimen, 6 mm. diameter, with medusa buds.

Net No. 935, 1,463-0 meters, September 23, 1930, 1 specimen, 10 mm. diameter, with gonads.

These specimens confirm conclusions earlier reached from the study of the more extensive *Bache* series (Bigelow, 1918, p. 368) as to the relationship of *B. niobe* to other species of the genus, for they fall well within the recorded range of *niobe* in number of marginal tentacles and in branching of the oral tentacles. As in previous collections, the smaller specimens, up to 9 mm. in diameter, bear the medusa buds well described by Mayer (1910), whereas the gonads have so far been found only in specimens of 8 mm. in diameter or larger. In the specimens listed above, as in those of the *Bache* collection, the sex-masses are adradial, in which *niobe* resembles *fulva* and *britannica*. It was not possible to determine on the *Bache* specimens whether or not the masses of sexual tissue were discontinous in the interradii, at the base of the manubrium. This, however, seems definitely to be the case in the specimen from Net No. 862; apparently so in the specimen from Net No. 812 (see list above). Hence, while the other two specimens with gonads are too much contracted to show this feature, it can now be added to the specific diagnosis.

The medusa buds in the smaller specimens add nothing to Mayer's (1910) account, except for confirmation.

I may note also that one specimen (Net No. 562) is infested with the parasitic larval stages of a Narcomedusa, probably *Cunoctantha.*

The large specimens are so much contracted that exact counting of the marginal tentacles is difficult. They appear to range from 13-14 up to 16; in one bundle possibly 18, the latter a somewhat greater number than reported previously. For this same reason, the number of branchings of the oral tentacles can be stated only tentatively; the maximum number of branchings appears to be not less than 8 or 9.

On the basis of cumulative evidence the following diagnosis may now be given for this species: Marginal tentacles, usual maximum 12-16 per bundle at sexual maturity, perhaps up to 18-19; gonads adradial, discontinuous in the interradii and entirely confined to the manubrium proper; manubrium sessile, i.e., there is no gelatinous peduncle; ocelli are present; oral tentacles branch a maximum of 7-9 times. Medium sized individuals may produce medusa-buds. It is not known whether the same individuals produce first buds, then gonads in succession, or whether some individuals exhibit the asexual reproduction only, others the sexual.

The closest ally of *niobe* is the wide-ranging Pacific species, *fulva;* so close in fact, that no constant difference has been found, to separate them, other than the common occurrence of budding in the former, its absence, so far as known, in the latter.

General Distribution: Records for *B. niobe* are so far confined to the waters between southern Florida, Cuba, the Bahamas, and Bermuda. The common occurrence of this species, close to the surface, proves it a shoal water form, hence it is probable that the specimens taken in deep hauls (all with open nets) were picked up not far below the surface.

PANDEIDAE.

Pandea.

Pandea conica Quoy and Gaimard.

Dianaea conica, Quoy and Gaimard, 1827, p. 182, Pl. 6A, Figs. 3-4.

For synonymy, see, Mayer, 1910, p. 118; Hartlaub, 1914, p. 338; Kramp, 1924, p. 8; Uchida, 1927, p. 214; Ranson, 1936, p. 84.

Material: Net No. 649, 1,646-0 meters, May 29, 1930, 1 specimen, about 17 mm. high.

The single example is much contracted, the margin being strongly recurved; gonads, radial canals, and tentacular bulbs are, however, in good condition, and it is chiefly on the basis of the former that the specimen is identified as *P. conica.*

The several recent accounts of this species agree that, at maturity, its gonads form an irregular net-work completely occupying the interradial areas of the gastric wall (see especially, Mayer, 1910, p. 117, Fig. 63B; Hartlaub, 1914, Figs. 283, 286; Uchida, 1927, Fig. 38; Ranson, 1936, Pl. 1, Fig. 2). Conditions in the present specimen suggest a somewhat more advanced stage in development, for while the upper portion of the manubrium shows much the type of network—the most distinctive generic feature—usually figured, this gives place in the distal zone next the lip to an irregular series of folds and knobs, a formation not shown in any of the earlier figures, though perhaps indicated by Uchida (1927).

There are 34 or 35 tentacles—a number falling well within the recorded range, the maximum so far recorded being 44 in a specimen 30 mm. high (Uchida, 1927). The tentacles also show the characteristic laterally compressed basal bulbs, each with a well marked, dark red, abaxial ocellus, repeatedly described for *P. conica.*

Earlier accounts have varied as to whether the walls of the radial canals are smooth (Hartlaub, 1914, p. 339), or more or less jagged (Mayer, 1910, p. 117, Fig. 63; Uchida, 1927, p. 214). In the present example, they are of the latter type, much as pictured by Uchida (1927) and reported by Kramp (1928) for a large specimen from Japan. The only feature specifically characteristic of *P. conica* that is not clearly shown is the ribbing of the exumbrella with nematocyst ridges. The bell does show a definite ridge in the radius of each tentacle. But the exumbral surface has been so badly rubbed, that one cannot be certain whether these ridges actually represent the locations of nematocyst ribs, or are merely contraction phenomena. But the specimen agrees so well in all other respects with the accounts of *conica,* and with good specimens of the latter from Naples, with which I have been able to compare it, that its identity, as such, seems assured.

General Distribution: *P. conica* has already been found at a station not far from Bermuda (Bigelow, 1918).[2] Other captures show a wide distribution, including many localities in the Mediterranean (Kramp, 1924), off Scotland, the South Atlantic, Japan, and the Philippines.

Vertical Range: Recorded depths of capture indicated that *P. conica* occupies a considerable depth zone, for while all stages have been found commonly at the surface (Kramp, 1924; Ranson, 1936), a fair proportion of the records have been from nets working down to considerable depths.[3] But the deep hauls yielding it have all been with open nets, nor are data extensive enough to allow any conclusion as to the lower limit to its normal occurrence.

---

[2] Identification of this specimen was provisional, but subsequent studies of *P. conica* show that it fell well within the varietal range of this species.

[3] See especially the table of *Thor* captures, given by Kramp (1924, p. 9).

Pandea rubra Bigelow.

Pandea rubra, Bigelow, 1913, p. 14, Pl. 2, Figs. 1-7; Hartlaub, 1914, p. 340; Kramp, 1920, p. 4; 1926, p. 96, Pl. 2, Fig. 15; Ranson, 1936, p. 81.

Material: Net No. 562, 914-0 meters, May 10, 1930, 1 specimen, about 25 mm. high.

Net No. 607, 914-0 meters, May 20, 1930, 1 specimen, about 40 mm. high.

Net No. 613, 1,097-0 meters, May 21, 1930, 1 specimen, about 40 mm. high.

Net No. 800 1,463-0 meters, July 15, 1930, 1 specimen, about 40 mm. high.

The specimens from Net Nos. 562, 613, and 800 are in good enough condition to show that they agree closely, even as to details, with the original series from the North Pacific, and with those subsequently collected in the North Atlantic by the *Armauer Hansen* (Kramp, 1920; 1926.) The most diagnostic morphological features of this species, as contrasted with its relative *P. conica,* are its lack of exumbral nettle ribs, the thin bell wall, the very complex and fine meshed network formed on the walls of the manubrium by the development of the gonads, the complexly crenulated lips, the small number of tentacles, and the large size attained at maturity. Another difference is that most accounts of *conica* credit it with ocelli, whereas such organs have not been detected in any of the specimens of *rubra* so far seen.

The largest example yet recorded (from the Pacific) about 75 mm. high, had about 20 tentacles (Bigelow, 1913); Pacific examples of 35-47 mm. had 14-18. Present indications are that the number of tentacles may average somewhat smaller in medium-sized examples from the Atlantic than from the Pacific, for in 2 Bermudian specimens about 38-40 mm. high, and in one of Kramp's (1920; 1926), of about the same size, the number ranged from 12-14. But larger series might well show that there is actually no regional difference in this respect. Specimens 25-31 mm. high (1 Pacific, 2 Atlantic) may have 8 (Kramp, 1926, p. 96), 9 (Bermudian specimen, Net No. 562), or 12 or 13 tentacles (Bigelow, 1913, Pl. 2, Fig. 6).

The gonads of *P. rubra* are extremely characteristic, the sexual convolutions of the manubrium taking the form of an extremely fine and numerous-meshed network; comparison of a photograph of a Pacific specimen (Bigelow, 1913, Pl. 2, Fig. 2)—which would equally well represent the Bermudian specimen from Net No. 613—with illustrations of *P. conica* by Mayer (1910, Fig. 63) and by Ranson (1936, Pl. 1, Fig. 2) will illustrate how widely the two species differ in this respect; how widely, in fact, *rubra* differs from any other pandeid yet known. Seen from the inner side, the sexual thickenings appear as a great number of knobs.

The most arresting feature of *P. rubra,* among its relatives, is that it shows extreme development of what might now be termed "bathypelagic" pigmentation. The Bermuda specimens about 40 mm. high show the same reddish or chocolate brown coloration as the Pacific specimens of the same size or larger, the entire manubrium, tentacles, and subumbrella surface being densely pigmented, with the more palely colored radial canals showing as pale bands. In the Bermudian example of 25 mm., however, in which the manubrium and tentacles are equally densely colored, the subumbrella is pigmented only in the immediate vicinity of the base of the manubrium, so that the pigmented canals—radial and circular—show as dark bands in the transparent bell, as was also the case in the smaller of the Pacific specimens. As Pacific examples of intermediate size (35-40 mm.) showed an intermediate stage (Bigelow, 1913, p. 16), it appears that it is not until the medusa is well-grown that pigment spreads out over the subumbrella—perhaps accompanying a descent into deeper water.

Ranson (1936, p. 82) does not consider the coloration diagnostic in this genus. The pigmentation of *P. rubra* is, however so peculiar in its density and opacity, and in its eventual extension over the subumbrella (quite apart from the precise shade of color), and *P. rubra* differs so widely in these respects from *P. conica,* that it must be regarded as a specific characteristic even though it may not be a safe criterion for identification except for large specimens.

General Distribution: Previous records include high latitudes in the northwest Pacific and Bering Sea (Bigelow, 1913); and, more recently, two oceanic stations to the west of Ireland (Kramp, 1920). The captures at Bermuda now make it likely that its range will finally prove to be as extensive as that of other bathypelagic medusae.

Vertical Range: The shoalest of the 6 hauls that have so far yielded it was from 411-0 meters (*Albatross* Sta. 4800); others have been from 549-0 meters or deeper.

BYTHOTIARIDAE.

Heterotiara.

Heterotiara anonyma Maas.

Heterotiara anonyma, Maas, 1905, p. 19, Pl. 3, Figs. 19-21; Bigelow, 1909, p. 216, Pl. 41, Figs. 12-13; 1913, p. 25; 1918, p. 382; Mayer, 1910, p. 107, 489; Vanhöffen, 1911, p. 211, Pl. 22, Figs. 3, 4; Hartlaub, 1914, p. 350.

Material: Net No. 79, 1,280-0 meters, May 8, 1929, 1 very fragmentary specimen, about 20 mm. high by 17 mm. in diameter.

Net No. 977, Surface, May 12, 1931, 1 specimen, 13 mm. high by 9 mm. in diameter, with 10 tentacles.

The specimen from Net No. 977 is in excellent condition. As regards size, in relation to the number of tentacles, it falls well within the range already recorded (Bigelow, 1913, p. 26; 1918, p. 382; 1919, p. 287.

The larger specimen is in such poor condition that identification is only tentative. Its general appearance seems, however, to warrant reference to *Heterotiara,* and its large size to *H. anonyma* rather than to *H. minor.*

General Distribution: Previous Atlantic records are between Florida, the Bahamas, and Cuba (Bigelow, 1918). Elsewhere, it is known from Malayan waters, the Indian Ocean and several localities in the Pacific, South and North, including Bering Sea (for list of Pacific localities, see Hartlaub, 1914, p. 351).

Vertical Range: The recorded vertical range includes various depths from the surface downward. The comparative frequency with which the *Bache* took it shoaler than 100 meters (Bigelow, 1918, p. 382), makes it likely that specimens from deep hauls with open nets were actually taken in the upper water layers.

Calycopsis.

Calycopsis sp.?

Material: Net No. 959, 914-0 meters, September 29, 1930, 1 specimen about 22 mm. high; 1 specimen, much crumpled, about 9 mm. high.

The larger specimen is fragmentary, having lost all but the cruciform base of the manubrium. And it apparently represents an abnormality of the same type as pictured by Kramp (1924, p. 15, Fig. 11B, 11D) for *Bythotiara murrayi,* for the canals are connected in an irregular network, the arrangement differing on the halves of the bell. To attempt to give it a specific name would only add to the difficulties with which the student of the genus is faced.

LEPTOMEDUSAE.

LAODICEIDAE.

Chromatonema.

The systematic location of this genus, originally described by Fewkes (1882), is still a moot question: it is placed by Kramp (1919; 1933) among the Laodiceidae, which by common consent, are the leptomedusan group most closely related to the higher Anthomedusae, whereas Ranson (1936) refers it to the latter, as a member of the Williidae. Discussion of this point necessarily revolves chiefly around the relationship of the gonads to the gastrovascular system, i.e., whether the perradial diverticula from the corners of the stomach, along which the sexual tissue is developed, are actually part of the manubrium, whether they are merely the dilated proximal sectors of the radial canals, or whether (as I believe) no sharp distinction can be drawn between gastric and canalar portions. This last view has already been proposed by Kramp (1933, p. 552) who says, for the Laodiceidae as a whole, that the separation of the gonads from the manubrium is not "durchgeführt." The Bermudian series are not in good enough condition to throw light on this point. But successive growth stages in the closely allied *C. erythrogonon,* from the Pacific (Bigelow, 1909), show, on the one hand, that the development of the gonads does take place along the radial canals (cf. Bigelow, 1909, Pl. 39, Fig. 6 with Figs. 2-3), but, on the other hand, that as the sex masses increase in size and complexity, the canal-sectors that they occupy expand in breadth and so become morphologically incorporated into the cruciform angles of the manubrium proper. Thus, it is only distal to the extremities of the gonads that the canals continue to retain their narrow tubular nature. It also seems probable from the corresponding expansion of entodermal pigment that Kramp (1919) was correct in crediting a digestive function to the expanded proximal portions.

If this view be correct, the primary question is no longer whether we are to regard *Chromatonema* as a Leptomedusa or as an Anthomedusa, for it bridges the gap, but to which of the borderline groups it belongs, or is most closely related. Basing the decision chiefly on the marginal sensory clubs, it seems wisest to follow Kramp (1919; 1933) in referring it to the Laodiceidae—at least, provisionally. But future study may well show that *Chromatonema* deserves a separate family, for as Kramp (1919) has emphasized, its gonads are fundamentally similar to those of *Calycopsis,* rather than to those of *Laodicea* or *Ptychogena.* I cannot follow Ranson (1936) in referring it to the Williidae (if his own definition of the latter is to be accepted), because he confines this family to forms lacking a circular canal, which is present in *Chromatonema* as Kramp (1919, p. 9) has shown and as Ranson (1936, p. 103) himself remarks, and because the typical members of the Williidae (*Willia* and *Proboscidactyla*) lack marginal organs other than tentacles.

Chromatonema rubrum Fewkes.

Chromatonema rubrum, Fewkes, 1882, p. 305, Pl. 1, Fig. 41.

For subsequent references, see Kramp, 1919, p. 7; 1933, p. 552; Ranson, 1936, p. 102.

Material: Net No. 368, 1,280-0 meters, August 14, 1929 and Net No.

959, 914-0 meters, September 29, 1930, 2 very fragmentary specimens, respectively about 17 and 15 mm. in diameter.

One of these specimens still bears fragments of a few tentacles, though no cordyli; the other has lost the marginal zone altogether. Identity seems, however, reasonably assured by what remains of the gonads, which are of very characteristic appearance in this genus.

The Bermuda capture extends the known range of *C. rubrum* southward, previous records being west of the Azores (Ranson, 1936); off the American continental slope in Latitude about 40° N. (Fewkes, 1882); and at numerous localities farther north, including Davis Strait (Kramp, 1919, Chart I, p. 13).

The depths of capture of the Bermudian specimens are in line with previous experience that *C. rubrum* inhabits chiefly the mid-depths, the great majority of captures (all with open nets) having been in hauls reaching down to at least 700 meters, and as Kramp (1933, p. 553) remarks "nur ein paarmal in höheren Wasserlagen."

AEQUORIDAE.

Aequorea.

The few Aequoreas in the collection represent the subdivision of the genus in which the stomach is only 1/4-1/5 as broad as the diameter of the disc. In contrast to the multiplicity of names under which large-stomached Aequoreas have appeared in literature, the small-stomached group includes only two named forms, *tenuis* and *floridana.* The first of these is now generally accepted as a good species (Bigelow, 1913; Kramp, 1933; Ranson, 1936), size of stomach having proved one of the most dependable characters in this widely variable genus. But the status of the second has remained doubtful, awaiting critical examination of the supposed differences—all minor—between it and *tenuis.* The Bermuda specimens agree so closely with A. Agassiz's (1865) account of *floridana* as to leave no doubt of their identity with the latter. And the need of giving them a name makes pertinent a decision as to the relationship of *floridana* to *tenuis;* names which appeared on the same page in the original publication. According to the original accounts, and to Mayer's (1910) more recent comparison, the chief differences between the two are that *floridana* has more tentacles at a smaller size, about four times as many otocysts as tentacles instead of an equal number, a somewhat smaller stomach (about 1/7 instead of 1/5 as wide as the diameter of the bell), and that its radial canals are very narrow, its tentacles minute.[4] Hargitt (1905), however, had already shown that in *tenuis* from Woods Hole (i.e., from the type region) numerical characters are all highly variable. Thus, a specimen of only 36 mm. may have even more tentacles than one of 47 mm. Canals not only vary in number, but show much irregular branching and anastomosis. The number of otocysts (described by A. Agassiz as alternating regularly with the tentacles) may be one, is often two, and sometimes even more between every two tentacles and series of typical *tenuis* from Woods Hole in the collection of the Museum of Comparative Zoology, similarly show from 1-4; most frequently 2 or 3; the number depending, it seems, on the distance apart of the large tentacles, and on how many rudimentary tentacles there are in the interspaces. I may note in passing, that while A. Agassiz (1865, p. 96, Fig. 138) stated that there is always a single otocyst between 2 tentacles in *tenuis,* the segment of margin he illustrated was one in which two large tentacles stood close together with no small ones intervening.

The contracted condition of the specimens in the present collection makes it difficult to make sure of the total number of otocysts. But in other specimens from Bermuda, in the collection of the Museum of Comparative Zoology, there are from one to three between every two large tentacles, most frequently one or two in the sectors on the margin on which the otocysts are still intact, which agrees with the Woods Hole specimens of *tenuis*. And the number of small tentacles, between 2 adjacent large ones, varies from none to an observed maximum of six, usually 1-3.

---

[4] Mayer's (1910, Pl. 43, Fig. 6) illustration of *Ae. floridana* is obviously labelled incorrectly, for it shows a very wide stomach.

Evidently, then, one can no longer invoke numerical precision in the number of otocysts relative to tentacles as an alternative character between *tenuis* and *floridana*. Neither can the number of large tentacles finally developed, for while, by published accounts, this is somewhat larger for *floridana* (up to 100) than for *tenuis* (up to 90), there is no discontinuity in this respect. Comparison of the Woods Hole series, just mentioned, with the Bermudian specimens shows, however, that at diameters of 24-35 mm. (*tenuis* is only half grown at this size), *tenuis* consistently has significantly fewer large tentacles than *floridana*, the number in the one case ranging from 43-58, in the other from 63-103. And a still sharper distinction appears in the number of canals, for while in the *tenuis* within this size range that I have examined, the number of complete canals arising from the stomach, varies from 22-31 (plus 1-4 blind centrifugals in 5 of the seven specimens), which corroborates previous reports of 24-32, the number in the Bermuda specimens is 16 in every specimen (large or small) where countable, except for two (respectively of 25 and 28 mm.) in which it is 15. And no blind centrifugals are to be seen in any. A. Agassiz's (1865, Fig. 139) illustration of *floridana* also shows 16 complete canals, though with one short centrifugal also, besides indications of an early stage in formation of several more, while Mayer (1910, p. 330) reports 16-24 complete canals.

Thus it appears that while occasional specimens of *floridana* may have as many canals as an occasional—perhaps stunted—*tenuis*, the number is usually only ½ to ⅔ as great in the former as in the latter, with strong indications of a normal determinate number of 16 in the one case, of 32 in the other. And this difference seems sufficient to warrant recognition of both species. A minor difference is that *floridana* (so far as known) is full grown and has its maximum number of large tentacles at a maximum reported diameter of only about 50 mm.; whereas *tenuis*, at Woods Hole, is known to reach a diameter of 100 mm. (Mayer, 1910, p. 332).

Aequorea floridana L. Agassiz.

Rhegmatodes floridanus, L. Agassiz, 1862, p. 361; A. Agassiz, 1865, p. 97, Fig. 139.

Rhegmatodes floridana, Haeckel, 1879, p. 223.

Aequorea floridana, Mayer, 1910, p. 330; Bigelow, 1913, p. 37; 1919, p. 309.

Material: Net No. 840, Surface, September 3, 1930, 1 specimen about 19-20 mm. in diameter, stomach diameter, 4 mm., 16 canals, 72 tentacles; 1 specimen, 23-24 mm. in diameter, stomach diameter about 5 mm., 16 canals and about 50 large tentacles. As the margin in each case is damaged, exact measurement of diameter is not possible.

Also, 16 other Bermudian specimens, 12-37 mm. in diameter (besides fragments) collected in the summers of 1903, 1904, 1911 and 1916, now in the Museum of Comparative Zoology.

The following tabulation for the Bermuda specimens is pertinent to the foregoing discussion of the relationship of *Ae. floridana* to *Ae. tenuis*.

Date of Collection.	Approximate Diameter.	Approximate Diameter of Stomach.	Approximate Number of Large Tentacles.	Canals.
1904	12	3	37	16
1904	15	3	45	16
1930	20	4	72	16
1930	23	5	50	16
1904	23	6	63	16
1904	25	5	67	16
1911	25	6	63	15
1911	28	7	46	15
1911	28	5	81	16
1911	33	7	74	16
1916	33	7	87	16
1916	33	7	85	?
1904	35	7-8	83	16
1916	37	8	103	16

Relative counts of large tentacles and of small cannot be precise, there being no sharp demarcation between the latter and rudimentary knobs of various sizes, the variety in size of which is evidence that while some would have developed into large, others would have remained permanently rudimentary.

The specimens of 12-15 mm. have no gonads; in those of 20-23 mm., gonads have appeared on the outer ⅓-½ of the radial canals; in those of 25-28 mm., they occupy the outer ½-⅔ and the outer ⅔-¾ in the larger specimens of 33-37 mm.

In *Ae. tenuis* of corresponding sizes, the gonads occupy about the same sectors of the canals, but with continued growth they finally come to occupy nearly the whole length of canals, though (as Mayer, 1910, p. 332, remarks) "not quite reaching the circular canal."

According to Mayer (1910, p. 330), the stomach is relatively smaller in *floridana* (only 1/7 as wide as the disc) than in *tenuis* (about 1/5 the width of the disc). However, A. Agassiz (1865, Fig. 139) pictures its greatest diameter as about 1/5. And as the preceding tabulation shows, it ranges about 1/4-1/5 the diameter of the disc in the Bermuda specimens. But since the stomach is rarely—if ever—circular, its breadth depends on what particular radius be chosen for measurement. Total diameter similarly depends on the degree of contraction (cupping) or relaxation of the disc.

General Distribution: So far as I am aware, previous records of small-stomached Aequoreas referable to *floridana* have been confined to the waters around the southern extremity of Florida. Bermuda is thus a considerable extension of the known range.

TRACHOMEDUSAE.

OLINDIIDAE.

Olindias.

Recent studies of considerable series from different parts of the world (Bigelow, 1909; 1919; Mayer, 1910; Neppi and Stiasny, 1913) have made it reasonably certain that the two named forms from the western Atlantic (*sambaquiensis* F. Müller and *tenuis* Fewkes) represent but a single species, for the supposed differences between them in number of tentacles, of marginal knobs, and of blind centripetal canals, and in the diameter of the disc indicate, at most, that *tenuis* is a dwarf race of *sambaquiensis*, or that the descriptions of the former have been based on specimens that had not attained their maximum growth and development. It has in fact been repeatedly suggested that both of these are simply varieties—if as much—of the well-known *O. phosphorica* of the Mediterranean. And the necessity of naming the Bermudian example listed below makes discussion of this question pertinent.

The only ostensible differences between *phosphorica* and *sambaquiensis* are that the original account of the latter (Müller, 1861) credits it with a larger number of secondary tentacles (200-300) and of centripetal canals (21-27 per quadrant), than have ever been recorded for *phosphorica,* for which the maxima are 100-120 tentacles and 19 centripetal canals in one quadrant (for tabulation of numerical characters, see Bigelow, 1909, p. 109; Mayer, 1910, p. 353). That is to say, *phosphorica* bears the same sort of relationship to *sambaquiensis* as does *tenuis* to *phosphorica.* By present indications it is not possible to make any definite specific separation, within this series, because the three forms intergrade in numerical characters. On the other hand, to unite the three definitely under one name, would obscure the very interesting fact that all the records from the West Indian-Bermudian region are for the *tenuis* (or to some extent paedogenetic) form, which is not known to occur at all in the Mediterranean. Neither, on the other hand, has *Olindias* from the latter sea, ever been found to attain the extreme development described for the Brazilian form. The case, analogous to that of the representatives of *Charybdea* from these same regions (p. 137), seems best handled taxonomically, by the recognition of subspecies. For further discussion of the reasons for this procedure, in the case of geographic races of medusae, see page 137.

Olindias phosphorica tenuis Fewkes.

Halicalyx tenuis, Fewkes, 1882, p. 277, Pl. 7, Fig. 15.

To the references given by Mayer, 1910, p. 354 ("*Olindias tenuis*"), add:

Olindias phosphorica [Partim], Bigelow, 1919, p. 317.

Olindias tenuis, Boone, 1933, p. 32.

Material: Net No. 840, Surface, September 20, 1929, 3 specimens, approximately 10, 10, and 25 mm. in diameter.

The larger specimen has large gonads, between 45 and 50 primary tentacles, and about 40 centripetal canals, the contracted and recurved state of the margin preventing exact enumeration. The chief interest of the series is as cumulative evidence that the Bermudian-West Indian representatives of *O. phosphorica* are characterized by fewer primary tentacles and canals at maturity than are their Mediterranean relatives; consequently that the recognition in nomenclature of *tenuis,* as a local subspecies, is justifiable. Owing to the condition of the large specimen, I was not able to count the secondary tentacles.

General Distribution: *O. tenuis* has already been reported from Bermuda (Bigelow, 1909, p. 109); other records are from the Bahamas and the coast of southern Florida (Fewkes, 1882; Mayer, 1910; Boone, 1933).

TRACHYNEMIDAE.

Rhopalonema.

Rhopalonema velatum Gegenbaur.

Rhopalonema velatum, Gegenbaur, 1856, p. 251, Pl. 9, Figs. 1-5.

For synonymy, see Bigelow, 1909, p. 129; Mayer, 1910, p. 378; Thiel, 1936, p. 10.

Material: Net Nos. 32, 35, 39, 43, 44, 67, 69, 97, 98, 100, 102, 362, 581, 620, 632, 634, 682, 720, 730, 793, 915, 916, 945, 959, 967; hauls at 549-0 to 1,829-0 meters; 39 specimens, 6-12 mm. in diameter; 1-5 specimens per haul.

These specimens, all of which are more or less fragmentary, call for no special comment, this being one of the best known of Trachomedusae. I need merely note that as all of them are large enough to show the situation of the gonads, there is no possibility that the list includes any examples of *Sminthea eurygaster*, a species somewhat similar in appearance, and which Thiel (1936, Fig. 2) has recently shown to be much more generally distributed on the high seas than formerly supposed.

General Distribution: *R. velatum* was to be expected near Bermuda, there being many previous records for the eastern side of the Sargasso Sea region, as well as elsewhere over the warmer belts of all three oceans, including also the Mediterranean and Red Sea. For a recent chart of distribution, see Thiel, 1936, Fig. 1.

It is interesting that 108 hauls shoaler than 549-0 meters did not yield it, for it often occurs close to the surface, with its center of abundance shoaler, in general, than 100 meters (Thiel, 1935, Fig. 21).

Pantachogon.

The definitions for this genus adopted by Mayer (1910), also recently by Broch (1929) and by Thiel (1932), would likewise include the medusa reported here (p. 117) as *Colobonema*. But for reasons stated on page 116, it seems to me preferable to retain the latter genus as distinct, because of the peculiar order in which its tentacles are developed, and because of the structure of its radial canals. The structure of its tentacles may perhaps be of generic significance, likewise. Opinions have also differed as to whether the generic limits of *Pantachogon* should be interpreted broadly enough to include the various species usually reported as *Homoeonema*, in which the gonads are localized along restricted sectors of the radial canals (Bigelow, 1913, p. 44), or should be restricted to forms in which these organs are developed more diffusely along the whole length of the canals (Broch, 1929; Thiel, 1932, 1936; Ranson, 1936). As the present collection contains representatives of the latter sort, only, it does not aid in the solution of this question.

The group with diffuse gonads includes three named forms, *haeckeli* (Maas, 1893), *rubrum* (Vanhöffen, 1902), and *scotti* (Browne, 1910). I have already expressed doubt as to whether the first two could be separated, the color being the only difference. As Ranson (1936) again emphasizes, successive studies of considerable series have revealed no anatomical differences whatever between them, hence he has now united them provisionally, Thiel (1936) definitely, and I believe with good reason. I may add that the capture near Bermuda of several specimens, lacking any trace of pigment (i.e., of the *haeckeli* type), now answers the last argument in favor of considering the two color-forms as distinct, i. e., that the colorless *haeckeli* was restricted to high latitudes. Nomenclatural rules require the choice of *haeckeli* Maas as the name for the joint species, because Maas' account, with clearly recognizable illustration showing the gonads and tentacles correctly, was published many years prior to the description of *rubrum* (Vanhöffen, 1902).

P. scotti, an Antarctic species, is separated from *haeckeli* by much more numerous tentacles (104-128, contrasted with a maximum of 64 in *haeckeli*). And so many specimens of the latter have now been examined that this difference seems established.

Pantachogon haeckeli Maas.

Pantachogon haeckeli, Maas, 1893, p. 17, Pl. 1, Fig. 2; 1904, p. 29; Mayer, 1910, p. 389; Bigelow, 1913, p. 44, Pl. 3, Figs. 4-8; Broch, 1929, p. 503; Thiel, 1932a, p. 152; 1936, p. 26.

Pantachogon rubrum, Vanhöffen, 1902a, p. 63, Pl. 9, Fig. 9, Pl. 10, Figs. 19-20, Pl. 11, Fig. 25; Maas, 1905, p. 55, Pl. 10, Fig. 66; Mayer, 1910, p. 389; Kramp, 1913, p. 274; 1914, p. 433; 1920, p. 5; 1924, p. 22; Bigelow, 1913, p. 44; Browne, 1916, p. 195; Broch, 1929, p. 504; Thiel, 1931, p. 330; 1932a, p. 153; Ranson, 1936, p. 147.

Pantachogon rubrum [Partim], Thiel, 1936, p. 24.

Material: Net Nos. 36, 42, 52, 64, 234, 296, 539, 552, 554, 575, 582, 598, 628, 648, 657, 658, 659, 666, 684, 685, 691, 695, 698, 709, 717, 718, 736, 739, 742, 757, 780, 789, 805, 809, 854, 862, 864, 866, 881, 897, 916, 964; 549-0 to 1,829-0 meters; 65 specimens; 1-5 per haul.

Also, 12 very fragmentary specimens, from Net Nos. 556, 640, 698, 709, 721, 748, 862, 929; 1,280-0 to 1,646-0 meters, are provisionally referred to this species.

The specimens are all more or less fragmentary—most of them very much damaged—but those included in the first of the two preceeding lists have enough of the margin and of the subumbrella intact to show that the tentacles are so spaced as to accord with the number characteristic of this species (maximum, 64), and that the radial canals are of even bore throughout their lengths. I have also been able to compare them with the series collected by the *Albatross* in the northwestern Pacific (Bigelow, 1913).

Tentacles: Vanhöffen (1902a) counted 7 tentacles per octant, between every two perradials, in all his specimens. Maas (1905), however, found smaller numbers in some octants, i.e., intermediate stages in development. And the Bermuda series again illustrates this, for while the sub-radials are seven in number in most of the octants in which complete counts can be made, only 6 are to be seen in some octants. And one specimen seems to have not more than 6 in any octant, i.e., a total of only 56. On the other hand, a greater number than 7 sub-radials has never been found in any octant, nor have additional tentacular bulbs been observed. That the number is determinant in *Pantachogon* (as it is in *Colobonema*) thus seems sufficiently established. The order of development of the different series of tentacles has not been traced; nor is this point clarified by the present series, preservation not being good enough for dependence to be placed on differences in size between different tentacles. It is, however, suggestive that a tentacle does not always stand exactly opposite a canal, i.e., it appears that in some cases none can be described as strictly "perradial;" neither are those most nearly opposite the canals appreciably larger than the others.

An interesting question, still awaiting answer, is whether the tentacles of *Pantachogon,* like those of *Colobonema,* are stump-like, as suggested by the fact that they have been very short, and of sub-equal length, in all the specimens so far examined, or whether Maas (1905) was correct in his suggestion that they are of ordinary filamentous type, but so easily broken off that all except the bases have been lost. None of the Bermudian and northwest Pacific specimens are in good enough condition to settle this point, though the general appearance of the tentacles—especially the fact that in many cases, they are square tipped—favors the second alternative.

Gonads: In one small specimen, about 8 mm. high, in which the gonads are intact, they represent about the same early stage in development illustrated for a North Pacific specimen of corresponding size (Bigelow, 1913, Pl. 3, Fig. 5). In the larger specimens, the gonads have either been lost entirely, or are represented by fragments only, here and there along the canals.

Musculature: The circular musculature of the subumbrella is strongly developed (Bigelow, 1913; Ranson, 1936); a development as striking, in fact, as it is in *Colobonema*. In *Pantachogon*, as in *Colobonema*, however, the musculature is not only entirely discontinuous along the lines of the radial canals, but terminates, apically, at the level where the general contour of the subumbrella changes from sub-cylindrical to domed, leaving a considerable clear space surrounding the base of the manubrium. And Ranson (1936) has recently pointed out that the outlines of the apical ends of the interradial muscular fields provide at least a specific character, being transversely truncate in *P. haeckeli*, as appears clearly in the few Bermuda specimens in which the musculature is still intact, whereas in *Colobonema* they are ovoid, corresponding to the contours of the interspaces between the apically expanded radial canals (p. 118). The latter, as Ranson (1936) has emphasized, are narrow and of uniform caliber, throughout their lengths, from bell margin to union with the manubrium, contrasting strongly with their state in *Colobonema*.

Color: Occasional specimens show a pinkish tinge. But the few in which the subumbral musculature is more or less intact are colorless: interesting evidence, as noted above (p. 114), that the unpigmented form of this species, as well as the rosy-colored, occurs in the warm belt of the North Atlantic. Thiel (1936, p. 24), in fact, has already shown that the two may exist side by side, the *Meteor* having taken one of each at a station in the South Atlantic. No recent student of *Pantachogon* has considered this color difference a sufficient ground *per se* for specific separation. But it is an interesting question, how the existence of the two color phases is to be interpreted. As the present series throws no light on this point, I need only note that the pigmentation of the rosy form (*P. rubrum*, auct.) is not of the peculiarly dense and opaque sort characteristic of many bathypelagic medusae.

General Distribution: Locality records for *P. haeckeli*, as here defined, are widespread in the Atlantic, including Spitzbergen, Irminger Sea and Davis Strait in the north, sundry localities off Ireland, in the Bay of Biscay, and in the region between the Canaries, Azores, and Gibralter; the Mediterranean; the eastern side of the tropical and South Atlantic south to Lat. 64° S.; the Antarctic (Weddell Sea); South and North Indian Oceans and Red Sea; Malaysia; and the extreme northern Pacific including Bering Sea and the Sea of Okhotsk. With the Bermuda records extending the known range to the western Sargasso Sea,—the nearest previous record was in mid-Atlantic—*P. haeckeli* is evidently world wide in the ocean basins, right up to the subpolar zones.

Vertical Range: The great majority of captures have been in open nets working as deep as 500-0 meters, the only exception being a single young specimen taken by the *Valdivia* in a haul from 60 meters (Vanhöffen, 1902).

Colobonema.

There has been much discussion recently as to whether *Colobonema* is generically separable from *Pantachogon*. Thiel (1936) at the one extreme, has even included its unique representative in the synonymy of *P. rubrum* (= *P. haeckeli*). But this seems definitely precluded not only by the constant difference in the number of tentacles, but also by the structure of the proximal sectors of the radial canals. Other students who have recently written of *Colobonema* (Bigelow, 1913; 1919; Kramp, 1924; Broch, 1929; Ranson, 1936) have therefore retained it as a separate genus, either definitely or provisionally. And that course is followed here.

The question what specific name should be applied to the one known representative of *Colobonema* is one that will not down, because a final answer depends on decision as to the accuracy, or the reverse, of the published description of a specimen no longer extant. Accepting Maas' (1905) subsequent statement that his earlier (1897) account of his *Homoeonema typicum,* which credited the latter with more than 32 tentacles, was an error resulting from the poor condition of the specimen, Mayer (1910), Uchida (1928), and I (Bigelow, 1913; 1919) have used this specific name, for in all other respects, Maas' *typicum* appears to resemble the form later described by Vanhöffen (1902a) as *Colobonema sericeum.* Kramp (1920; 1924), Broch (1929), and Ranson (1936), however, take the opposite view, that Maas' (1897) original *typicum* cannot be identified with *sericeum,* hence use the latter name.[5]

The present series adds nothing toward solution of this nomenclatural puzzle, beyond the opportunity for pointing out that choice of *typicum* as the specific designation has the advantage of providing a resting place for a name which is likely otherwise to remain permanently without connection with any actually existant medusa.

Colobonema typicum Maas.

Homoeonema typicum, Maas, 1897, p. 22, Pl. 3, Figs. 1-3.

For early synonymy, see Mayer, 1910, p. 385.

It has been referred to, subsequently, under the following names:

Colobonema sericeum, Kramp, 1920, p. 5; 1924, p. 28; Ranson, 1936, p. 152, Pl. 2, Figs. 14-15.

Homoeonema (*Colobonema*) *sericeum,* Broch, 1929, p. 500.

Colobonema typicum, Bigelow, 1913, p. 46; 1919, p. 322.

Homoeonema typicum, Uchida, 1928, p. 81.

Material: Net Nos. 26, 39, 94, 95, 99, 105, 240, 292, 293, 295, 296, 400, 434, 565, 597, 605, 606, 607, 610, 625, 626, 637, 641, 653, 680, 732, 760, 777, 802, 805, 813, 853, 867, 874, 937, 939, 964; 732-0 to 1,829-0 meters; 47 specimens; 1-3 per haul, mostly in poor condition.

The specimens range from about 8 to about 33 mm. in heighth. Features especially to be examined on any considerable series of this species that may now come to hand, are: (a), number and order of appearance of the tentacles, whether as constant as earlier records have indicated; (b), number of otocysts; and (c), contours of the proximal parts of the radial canals, which Ranson (1936, Pl. 2, Fig. 14) has found to differ significantly from those of *Pantachogon.*

Tentacles: Successive examinations have yielded cumulative evidence, not only that the final number of tentacles in this species is 32, but that variations from this number are so unusual that none has been found among 123 specimens collected by the *Valdivia* (Vanhöffen, 1902a) *Siboga* (Maas, 1905), *Research* (Browne, 1906), *Albatross* (Bigelow, 1909; 1913; 1919), *Thor* (Kramp, 1924), and by the Prince of Monaco (Ranson, 1936). The peculiar order of development—perradials, adradials, and finally interradials —first reported by Maas (1905), has proved equally unvarying, judging from the relative sizes of the different orders of tentacles on small and medium-sized specimens. Both these findings are further corroborated by the present series, for in every octant on which they can be counted, there is the usual interradial, and pair of adradials in the larger specimens. In one of the smaller specimens about 20 mm. high (Net No. 26), the interradial has not yet appeared in one of the octants, while in 6 of the other octants[6] it is represented by a rudimentary knob only, illustrating a stage between that in which the per- and adradials alone have appeared (Maas,

---

[5] The species subsequently described by Maas (1905) from the *Siboga* collection, as *typicum,* undoubtedly was identical with Vanhöffen's *sericeum.*

[6] The margin of the eighth octant has been torn off.

1905, Fig. 64), and the final stage in which the interradials are also well developed.

In all specimens so far examined (including the Bermuda series) the tentacles have been short, stump-like. And it seems now established that this is normal, and not the result of mutilation, for in the better preserved specimens the tips are rounded and apparently uninjured, i.e., with their ectodermal covering complete. And the fact that in large specimens the members of the per- and adradial series (sometimes the interradials also) are all about equal in length, suggests that they are but little extensible.

Otocysts: The otocysts of this species must be very easily detached, for only in one case has a single otocyst been detected, among the earlier collections (Bigelow, 1919, p. 323). One of the Bermuda specimens (Net No. 26) also bears one otocyst—agreeing in structure with the earlier account—between a per- and an adradial tentacle. But I have not been able to detect even a trace of any others, in this, or on any of the other specimens. To determine positively whether otocysts normally alternate with tentacles, as earlier observations suggest (Bigelow, 1913, p. 321), requires examination of specimens with undamaged margin.

Radial Canals: Ranson (1936, p. 154, Pl. 2, Fig. 14) has recently pointed out (what seems to have been overlooked previously) that the radial canals of *Colobonema* are expanded proximally so that their walls are in close contact (though discontinuous) in the interradii across the domed apex of the subumbrella, narrowing again toward their union with the narrow base of the manubrium, which gives characteristic ovoid contours to the apical ends of the 8 muscular zones. The better preserved of the Bermuda series corroborate this interpretation, so far as can be determined from surface views, though in all cases the base of the stomach is damaged.

General Distribution: *Colobonema*, as distinguished from *Pantachon haeckeli*[7] had been taken already at many stations in regions as widely scattered, as the central Sargasso Sea; the eastern North Atlantic; west of Ireland; between the Azores, Canaries, and the coast of Spain; Straits of Gibraltar; Mediterranean; equatorial and South Atlantic down to Latitude 42°S.; the Indian Ocean from Lat. 9°N. to Lat 34°S.; Malaysian region; Philippines; Japanese waters; and the eastern tropical Pacific. It is, in short, cosmopolitan in the warm and temperate belts, at appropriate depths, but has not yet been reported from Arctic or from Antarctic latitudes.

Vertical Range: So far as I have been able to learn, the shoalest haul that has so far yielded *Colobonema* was with an open net, from about 241-0 meters, most of the captures (all but one with open nets) being from hauls deeper than 500-0 meters; and there is one record from a closing net from 900-1,500 meters. Its bathypelagic habit is thus well established.

Crossota.

Crossota, originally classed with the Ptychogastridae (Vanhöffen, 1902a; Bigelow, 1909), was soon shown to be a trachynemid (Bigelow, 1913). But it is not yet possible to give any precise generic definition for it that can be depended upon to stand the test of time. During the first years of its history it was, indeed, regarded as a very sharply defined genus, for while the type species (*C. brunnea* Vanhöffen) agrees with *Aglaura* and *Aglantha* in the structure of the gonads, it differs markedly from them not only in lacking any trace of a gelatinous peduncle, but also—and from all other Trachynemidae as well—in having more than one row of tentacles. Shortly, however, other species were described, one of which (*rufobrunnea*, Kramp, 1913) apparently had the tentacles in a single row,[8] while in another (*C.*

---

[7] Thiel's (1936) chart of distribution for *Pantachogon* also includes the *Colobonema* records, for he classes the latter as a synonym of the former.

[8] Broch (1929, p. 506) says "Ersichtlich in einer Reihe."

pedunculata Bigelow, 1913), there is a short gelatinous peduncle. The former partially bridges the gap between *Crossota* and *Pantachogon*, the latter between *Crossota* and *Aglantha*, i.e., between the subfamilies Rhopaloneminae and Aglaurinae, as defined by Broch (1929) and by Thiel (1936, p. 9). Indeed, *pedunculata* is tentatively referred to *Aglantha* by Thiel (1936, p. 22). But this course would involve expanding that genus to include species with tentacles in more than one series, for in *C. pedunculata* these are in three or four irregular rows, much as in *Crossota brunnea*. Until Kramp and Damas' (1925, p. 317) characterization of the tentacles of *norvegica* as being in a single row is confirmed, it seems simplest to confine *Crossota* to Trachynemidae with sausage-shaped gonads hanging free from the subumbrella and with many closely crowded tentacles, in more than one row, irrespective of whether or not there is a short peduncle. Data as to the number of otocysts is much to be desired. In the only species in which any estimate of this has been possible, they have proved much more numerous than they are in *Aglantha*.

? **Crossota brunnea** Vanhöffen.

Crossota brunnea, Vanhöffen, 1902a, p. 73, Pl. 9, Figs. 11-13, Pl. 12, Figs. 34-38, 43-47; Bigelow, 1909, p. 135, Pl. 2, Fig. 7, Pl. 45, Fig. 9; Mayer, 1910, p. 396.

Crossota brunnea [Partim], Thiel, 1936, p. 20[9].

Crossota brunnea, var. *norvegica*, Bigelow, 1913, p. 48.

Crossota norvegica, Broch, 1929, p. 507.

? *Crossota norvegica*, Kramp, 1920, p. 5.

Non *Crossota norvegica*, Vanhöffen, 1902a, p. 75; Kramp and Damas, 1925, p. 317.

See Thiel (1936, p. 21) for a recent summary of the checkered history of *C. norvegica* Vanhöffen and for the reasons why *norvegica* cannot be used as the name for a variety of *C. brunnea* as I formerly did (Bigelow, 1913).

Material: Net Nos. 241, 642, 665, 733, 787, 794, 854, 869; 1,097-0 to 1,829-0 meters; 11 very fragmentary specimens, all approximately 14 mm. in diameter.

These specimens are all in such poor condition that identification is only tentative; in every case all trace of the manubrium and gonads has been lost and only faint indications of the radial canals are to be seen. At first sight, it seemed that they might belong to *C. rufobrunnea* Kramp, for in most cases the tentacular bases—in their present state—have the appearance of being in a single row. But in one specimen in which the margin is in somewhat better condition than in the others, the larger (older) tentacle-bases arise at a slightly higher level than do the smaller (younger) ones, for which reason it seems more probable that the whole series belongs to *C. brunnea*. In some parts of the margin, 3 successive sizes—or rows—of tentacles can be recognized, in others only two, as was the case in the *Meteor* specimen recently described by Thiel (1936, p. 20). In the specimens of *brunnea* that I have seen, in good enough condition to show the tentacles (Bigelow, 1909; 1913), the arrangement in different rows has been less regular than Vanhöffen (1902a, Pl. 12, Fig. 47) pictured it, the tentacles being more crowded and the older only a very short distance above the younger, instead of well above the latter: this distribution is more correctly represented in Vanhöffen's 1902a, Pl. 12, Fig. 46) section of the margin.

---

[9] Thiel (1936) includes *C. alba* Bigelow in the synonymy of *C. brunnea*.

It was not possible to make a reliable count of the tentacles, even in any one octant, owing to the uncertainty as to the precise location of the radial canals. In the specimen just mentioned, the spacings of the tentacular-bases suggests a total of at least 200. No otocysts were to be found.

In most of the specimens enough of the subumbral pigmentation is still intact to show that it was of the characteristic opacity and chocolate or reddish brown color.

General Distribution: Previous records probably referable to *C. brunnea*, as mapped by Thiel (1936, p. 23), are widely scattered in the eastern side of the Atlantic from Latitude about 50° N. down to the Antarctic—extended, now in all probability to the western half of the Sargasso Sea—; in both sides of the Indian Ocean; and in the parts of the eastern tropical and far northern Pacific traversed by the *Albatross* on the cruises of 1904-1905 and 1906. It has not been taken, however, in the Mediterranean. And while reaching high latitudes in the south, it apparently does not inhabit the North Polar regions.

Vertical Range: All captures have been in deep hauls.

? **Crossota.**

The following fragments (now mere shells) are tentatively referred to *Crossota* because such indications of the locations of the tentacles as are still to be seen suggest that these were numerous and close crowded, and because most of the specimens still show some trace of subumbral pigment. But specific identification is out of the question.

Net Nos. 41, 66, 74, 75, 101, 114, 137, 138, 220, 295, 640, 644, 647, 666, 724, 748, 770, 779, 807, 812, 815, 844, 849, 867, 885, 891, 917, 935, 959, 967, 970; 914-0 to 1,830-0 meters; fragments of 37 specimens.

TRACHYNEMIDAE gen. ?

Medusae, apparently belonging to the Trachynemidae, but in such poor condition as to preclude even provisional identification, were taken in Net Nos. 110, 145, 269, 295, 317, 322, 327, 341, 449, 574, 577, 598, 613, 644, 680, 715, 718, 726, 738, 767, 785, 795, 799, 807, 824, 827, 867, 882, 885, 896, 926, 968; a total of 51 specimens, 1-4 per haul.

HALICREIDAE.

Halicreas.

Opinions have differed whether such of the Halicreidae as have only 8 canals, and tentacles in a continuous row (i.e., not grouped as they are in *Botrynema*) should all be referred to the one genus, *Halicreas*, or to two genera; and if the latter, whether generic separation should be based on number of tentacles alone, as by Vanhöffen (1902a), on this character combined with the form of the umbrella, as by Ranson (1936); or on the presence or absence of exumbral papillae, as formerly by me (1909).

Even granting eventual agreement as to the relative taxonomic value of different characters, we still face a nomenclatural difficulty (if two genera are to be recognized), in the fact that the decision as to the correct name of the second genus would depend on the true identity of the specimen originally described by Maas (1893) as *Homoeonema platygonon*, and later declared by him (Maas, 1906, p. 3) to be a halicreasid, not a trachynemid as he originally supposed.

Examination of the type specimen of *H. platygonon*, if this be still in existence, would settle the point. Meanwhile it seems simplest to follow Broch (1929) and Thiel (1936), in uniting, in *Halicreas*, all halicreasids with 8 canals and continuous series of tentacles, whether the exumbrella be papillate or smooth, and whether the tentacles be few or numerous, all of one size, or of two sizes. For further discussion, see Ranson (1936) and Thiel (1936).

Among the named forms referable to *Halicreas* as thus expanded, two (*H. minimum* Fewkes and *H. papillosum* Vanhöffen) are set apart by the presence of exumbral papillae. Thiel (1936), it is true, bases the specific distinction within *Halicreas* solely on whether the tentacles are of one size or of two sizes. I see no reason, however, for abandoning the presence or absence of exumbral papillae as of specific value here, even if it be not of generic worth as I formerly suggested; not only are these structures highly distinctive features, but no variation has ever been found in their number. And Ranson (1936) also considers them as specific.

H. papillosum is the best-known member of the genus, and large series of it have been taken on most of the recent expeditions that have done deep towing. It has, however, long been generally recognized that it might eventually prove to be identical with the *H. minimum* of Fewkes (type species of the genus) which was described 20 years the earlier, consequently *minimum* has repeatedly been classed as a doubtful synonym of *papillosum* in the lists of references to the latter. Fortunately, the collection of the Museum of Comparative Zoology contains one of Fewkes' original two specimens (previously overlooked); evidently the one described by him (1882, p. 306) as "expanded" and "preserved in spirit." Although this specimen has subsequently been dessicated, then restored to alcohol, the typical exumbral papillae (each with several conical projections) are still to be seen, while the locations of the 8 radial canals are marked as broad, flat ridges on the subumbrella. And fragments of the circular lip are still recognizable. What Fewkes took for the velum was in reality the marginal zone of the bell, distal to the exumbral papillae. Thus, while the tentacles have all been lost —as indeed Fewkes pointed out—there is no reason to doubt that it is the same species that Vanhöffen (1902a) later described as *papillosum*, while Fewkes' specimens were from a locality where many *papillosum* have since been taken, on the cruises of the Woods Hole Oceanographic Institution. Consequently, there need no longer be any hesitancy in superseding *papillosum* by *minimum*, thus making one more step toward stability in the nomenclature of the medusae.

It has long been obvious that the five named representatives of the smooth-belled subdivision of the genus (*conicum*, *album*, *glabrum* and *rotundatum* Vanhöffen, 1902a; *racovitzae* Maas, 1906) stand in need of drastic reduction, successive studies (Bigelow, 1909; Ranson, 1936) having proved that the features on which Vanhöffen (1902a) laid chief stress (degree of doming of the exumbrella, and precise location of the gonads on the radial canals), are too variable to be of taxonomic significance. Thiel's (1936) recent grouping, based on whether there are two sizes of tentacles or only one, is a decided advance. It is certain that the tentacles are all alike in *racovitzae*, for Maas (1906) definitely states as much; likewise in *conicum* (Vanhöffen, 1902a, Pl. 11, Fig. 33). On the other hand, it seems equally certain that the original specimens of *glabrum* had tentacles of two sizes, because Vanhöffen (1902a, p. 70) describes them as "ebenso wie bei *H. papillosum* angeordnet." Hence—as *glabrum* has page priority in Vanhöffen's original paper—this name may be accepted for smooth-belled *Halicreas* with 2 sizes of tentacles.

Unfortunately, Vanhöffen gave no definite information on this point, either for his *Halicreas album* or his *Halicreas rotundatum*. The first of these is placed by Thiel (1936) in the group in which the tentacles are all of one size (i.e., grouped with *racovitzae* and *conicum*). And the original accounts certainly would allow this interpretation. But Vanhöffen's (1902a, p. 68) statement that "so wohl *Halicreas* wie *Haliscera*" has tentacles of two sizes, makes it seem more likely that this was true of his specimens of *album* and *rotundatum*. Hence it seems justifiable to class these names provisionally as synonyms of *glabrum*, recognizing, however, that the wide variation in numbers of tentacles between the several forms may finally warrant a further subdivision on this basis.

Halicreas minimum Fewkes.

Halicreas minimum, Fewkes, 1882, p. 306.

Halicreas papillosum, Vanhöffen, 1902a, p. 68, Pl. 9, Figs. 7-8; Pl. 11, Fig. 30.

For the more important subsequent references, see *Halicreas papillosum*, Mayer, 1910, p. 391; Ranson, 1936, p. 164; *Halicreas papillosum* [Partim], Thiel, 1936, p. 34.

Material: Net Nos. 25, 26, 41, 43, 44, 56, 60, 62, 65, 66, 67, 68, 69, 75, 76, 81, 83, 108, 110, 115, 124, 138, 144, 157, 203, 241, 247, 269, 270, 271, 293, 295, 297, 357, 360, 383, 401, 405, 406, 442, 466, 468, 481, 488, 501, 566, 569, 570, 576, 590, 599, 640, 648, 654, 682, 683, 684, 701, 703, 717, 718, 722, 723, 724, 727, 728, 730, 736, 741, 746, 750, 751, 756, 765, 767, 774, 781, 787, 788, 795, 799, 815, 852, 857, 858, 863, 864, 869, 875, 887, 893, 898, 919, 931, 932, 933, 935, 940, 942, 947, 963, 969, 970; at depths ranging from 0 to 2,012-0 meters; a total of 186 specimens; 1-6 specimens per haul, except for one catch of 17 specimens in Net No. 271.

The specimens, ranging from about 13 mm. to about 36 mm. in diameter, are all fragmentary, having lost every trace of marginal organs and of the gastrovascular system. Hence, they add nothing to previous accounts of the morphology of this interesting bathypelagic medusa. This species is, however, made so easily recognizable by the marginal papillae—structures so resistant that they persist even after the roughest handling—that identity seems assured. Most of them also show more or less trace of the gelatinous apical projection, though the discs of others are apically rounded, in their present condition.

General Distribution: Earlier records of capture are widespread over the eastern side of the tropical Pacific, also the tropical and subantarctic belts of the Indian Ocean, the East Indies and Philippines, Japan, Sea of Okhotsk, Bering Sea, the South Atlantic down to the Antarctic, north boreal and east temperate belts of the North Atlantic (Thiel, 1935, Fig 38; 1936, p. 36, Fig. 7; Ranson, 1936). It had been taken on the continental slope of America in the offing of Woods Hole. Curiously, however, there was no previous record of it in the Sargasso Sea region. The Bermuda records, proving it abundant there, are therefore interesting as cumulative evidence that it is cosmopolitan in the ocean basins at suitable depths, at low and mid-latitudes.

However, it has not been taken in the Mediterranean, in spite of the great number and wide distribution of deep hauls that have been made there by the *Thor* and by the Prince of Monaco (Kramp, 1924; Ranson, 1936). And its absence, or at least rarity, there is puzzling, for the comparative frequency of records from small depths at low latitudes in the Atlantic (see below), makes it unlikely that the shoalness of the sill depth of the Straits of Gibraltar can offer a permanent barrier to its entrance into the Mediterranean, as it apparently does in the case of certain more strictly bathypelagic animals (Bigelow and Sears, 1937, p. 128). For further discussion of its distribution and dispersal in the South Atlantic, see Thiel, 1935, p. 72.

Seasonal Distribution: The seasonal distribution of the hauls yielding *H. minima*, for the two years combined, appear from the following tabulation:

Month.	Hauls Yielding *H. minimum.*	Total Hauls, 1,280-0 Meters or Deeper.	% Yielding *H. minimum.*
April.	6	20	30
May.	24	77	31
June.	22	135	16
July.	17	109	15
August.	5	40	12
September.	29	158	19

This shows a somewhat greater abundance in spring, for the two collecting seasons combined, than during the summer months.

Vertical Range: The early records were all from hauls with open nets, leaving in doubt the precise depths from which the specimens came, but the great majority of the catches were from hauls that sampled down to 500 meters or deeper. Thus, the shoalest of the 40 *Valdivia* hauls that yielded specimens positively identified as *H. minimum* was from 600-0 meters, 37 of them at least 1,000-0 meters[10] or deeper (Vanhöffen, 1902). All of the 30 *Albatross* catches were, similarly, in hauls from 550-0 meters (Bigelow, 1909; 1913; 1919), while the records of the Prince of Monaco were all from 1,000-0 meters or deeper (Ranson, 1936).

The *Meteor* records have shown, however, that *H. minimum* is not exclusively restricted to great depths, but may populate the whole column from, say, 75 meters down to 800-900 meters, as appears from the distribution of catches in closing nets, tabulated below, from data presented by Thiel (1935, Tables 10, 21, Fig. 27; 1936, p. 34):

Depth in Meters.	Number of Cases.	Number of Specimens.
50- 70	1	1
50-100	7	8
100-200	2	2
200-400	5	7
400-600	4	5
600-800	2	1

And still more recent captures by *Atlantis* of the Woods Hole Oceanographic Institution make it unlikely that there is any definite lower boundary to its occurrence, any more than for various siphonophores (Bigelow and Sears, 1937, p. 137), for horizontal closing net hauls of uniform duration at 3 stations as described by Leavitt (1935) in the summer of 1935, yielded the following catches:

Depth in Meters.	Number of Cases.	Number of Specimens.
600	1	6
1,200	1	4
1,800	1	3
2,000	1	2
2,200	2	2

---

[10] One juvenile, perhaps of this identity, was taken at 200-0 meters.

The Bermuda collection amplifies the foregoing, proving that *H. minimum* may occasionally come right up to the surface (Net No. 654, 1 specimen). But in this part of the Sargasso Sea, where the thickness of the superficial stratum of warm water is great, the chief center of abundance lies deeper than in most parts of the oceans, or at least as deep as 1,400-1,800 meters, as appears from the following tabulation for the two seasons combined:

Depth in Meters.	No. of Hauls with *minimum.*	Total Number Hauls.	% with *minimum.*
732-0	2	40	5
913-0	3	132	2
1,097-0	2	134	2
1,280-0	8	132	6
1,463-0	21	132	15
1,646-0	34	135	25
1,829-0	31	135	22
2,012-0	3	4	45

H. minimum (seemingly also *H. glabrum* and *Halitrephes*) thus is a marked exception to the general rule that medusae having their center of abundance so deep, are densely pigmented.

Thiel (1935, p. 47) has shown, from the catches made in closing nets by the *Meteor,* that the individuals of the genus *Halicreas,* as a whole, average larger, the greater the depth. This suggests that the young stages are passed chiefly in the shoaler strata and that the medusae tend to sink as they grow larger. But we still await positive evidence whether the eggs, as a whole, rise to the surface, as he suggests (Thiel, 1935, p. 72).

? **Halicreas glabrum** Vanhöffen.

Halicreas glabrum, Vanhöffen, 1902a, p. 70, Pl. 9, Fig. 3; Mayer, 1910, p. 392; Ranson, 1936, p. 167.

Homoeonema glabrum, Bigelow and Leslie, 1930, p. 564.

Haliscera alba, Vanhöffen, 1902a, p. 71, Pl. 9, Fig. 5.

Homoeonema alba, Bigelow, 1909, p. 142, Pl. 3, Fig. 1-2, Pl. 33, Figs. 6, 11, Pl. 34, Fig. 9.

Halicreas album [Partim], Thiel, 1935, p. 48; 1936, p. 37.

Halicreas rotundatum, Vanhöffen, 1902a, p. 71, Pl. 9, Fig. 4; Maas, 1905, p. 57; Mayer, 1910, p. 392.

Halicreas papillosum [Partim], Thiel, 1936, p. 34. [Non *H. papillosum,* Vanhöffen, 1902.]

Material: Net Nos. 25, 43, 56, 62, 68, 75, 83, 89, 106, 114, 144, 145, 157, 218, 242, 247, 269, 270, 271, 295, 297, 315, 339, 345, 346, 347, 354, 359, 449, 466, 488, 501, 506, 539, 710, 742, 890, 942, 962; hauls from 914-0 meters to 2,012-0 meters; 66 specimens, 1-5 per haul.

These specimens—like Ranson's—agree very closely with Vanhöffen's (1902, p. 9, Fig. 3) illustration of *H. album* in the form of the bell, with high conical apex, and thin marginal zone, without any sign of the exumbral protuberances. But as already suggested (Bigelow and Leslie, 1930, p. 564), and as indicated above (p. 122), it is probable that *album* is specifically identical with Vanhöffen's *H. glabrum* and the latter name has page priority.

In every case, all trace of all the tentacles has been lost, preventing positive identification; in fact the great majority are mere shells. But in a few, parts of the subumbrella still remain. And one from Net No. 890, another from Net No. 942, are especially interesting, being in good enough condition to show the oval gonads situated proximally, leaving the distal parts of the radial canals free, as was the case in the *Albatross* specimens (Bigelow, 1909). And this corroborates Ranson's (1936, p. 168) observation that in his specimens (which had lost the gonads) the traces of the radial canals suggested proximal enlargements.

General Distribution: Previous records positively referable to *glabrum* + *album* are from the vicinity of the Azores (Ranson, 1936); and scattered along the route of the *Valdivia* in the eastern side of the Atlantic, from the offing of Morocco to Lat. 42° S., besides one locality record for the southern Indian Ocean (Vanhöffen, 1902a); several in the eastern tropical Pacific (Bigelow, 1909)[11]; and off California (Bigelow and Leslie, 1930). With the Bermuda records extending its known range to the western side of the North Atlantic, there seems no reason to doubt that the distribution of *H. glabrum* will eventually prove to be as wide as that of its better known relative, *H. minimum* (p. 122).

Vertical Range: It is not yet possible to make a final statement as to the vertical distribution of *H. glabrum,* as here defined, because it is combined with *H. racovitzae* and *H. conicum* in Thiel's (1935, 1936) discussions of the *Meteor* closing-net data. However, the fact that the *Valdivia, Albatross,* and Bermudian specimens all came from (open net) hauls from 550-0 meters, or deeper, suggests that it is chiefly bathypelagic in habit, though perhaps not exclusively so.

Halitrephes.

This genus, closely allied to *Halicreas* by the structure of the tentacles and of the sense organs, as well as by the simple circular mouth, without separate lips, but separated from it by the large number of radial canals, was first described from the collection made by the *Albatross* in the eastern tropical Pacific as *H. maasi* (Bigelow, 1909, p. 146, Pl. 33, Figs. 1-5, 7, 10, Pl. 45, Fig. 13). In the type specimen of the latter, 55 mm. in diameter, 28 canals were given off from the stomach, 5 of them branching dichotomously so that the number at the bell margin was 33; and there were about 70 tentacles of different sizes. Three years later, Vanhöffen (1912) described a second species, as *H. valdiviae,* from the collection of the German South Polar Expedition, with as many tentacles or even more, but separated from *maasi* by having only 16 canals. As the specimens examined by him ranged in diameter from 18 to 70 mm.—i.e., included full grown individuals as well as juveniles—the specific distinction seems well founded.

As the genus has not been seen since, the captures listed below from Bermuda are of interest, for although the specimens are extremely fragmentary, their identity seems reasonably certain.

Halitrephes valdiviae Vanhöffen.

Halitrephes valdiviae, Vanhöffen, 1912, p. 384.

Material: Net Nos. 135, 154, 247, 357, 451, 562, 580, 614, 635, 709, 714, 745, 767, 778, 818, 830, 843, 967; hauls from 914-0 to 1,829-0 meters; 19 specimens about 30 to 80 mm. in diameter.

All the specimens are in poor condition. Even when much battered, however, the flat, lenticular form, but with central thickening, combined with numerous endodermal tentacular roots, (which are so resistant that they are recognizable even in the most fragmentary specimens), give a general aspect so characteristic as to make *Halitrephes* easily recognizable, even when the canals have been lost. And the two known species differ so widely in the number of tentacles that in most cases a specimen is referable either to the one or to the other, with reasonable certainty. All of the Bermudian specimens show the endodermal roots of some of the tentacles; and in one example, several tentacles are still sufficiently intact to show the contrast between stiff distal, and soft proximal, portions, characteristic of the Halicreidae. It was not possible to make certain of the total number of tentacles, in any specimen. But the minimum number (specimen of about 55 mm.) was certainly as great as 102. In another of 45 mm., there were at least 105, while in others of 60-80 mm., 145-170 tentacular roots were counted, total numbers being evidently somewhat greater. This corresponds well to the distribution with size recorded by Vanhöffen (1912) of 32 tentacles in a specimen of 12 mm.; 32-64 tentacles at a diameter of 18-20 mm.; 64-96 at a diameter of 30-40 mm.; and 200 at 70 mm. As pointed out for *H. maasi* (Bigelow, 1909, p. 146), the tentacular bases are of various sizes, indicating their successive development. But as no trace of canals is to be seen in the marginal zone of any of the Bermudian specimens, nothing can be said as to the order of development of tentacles relative to canals.

---

[11] Thiel's (1936, p. 36) chart of distribution also includes locality records for *racovitzae* and *conicum.*

In one specimen, a sector of the margin still bears several rhopalia, alternating with the tentacular roots, as is the case in *H. maasi*, and agreeing closely with the rhopalia of the latter in structure and club-like appearance (Bigelow, 1909, Pl. 33, Fig. 10). The only example in which there is any trace of the gastrovascular system still to be seen, shows the circular lip characteristic of the genus and its allies, with the bases of about 8, at, broad canals in about one-half the circumference, suggesting a total of about sixteen; or the same number described by Vanhöffen (1912) for the original series of *H. valdiviae.*

General Distribution: The original collections of *H. valdiviae* were from the tropical Atlantic between Lat. 6° N. and Lat. 20° S.; and from the Indian Ocean between Lat. 2° N. and Lat. 34° S. The Bermuda captures are thus the most northerly yet recorded, and the farthest extra-tropical for the Atlantic. Present indications are that this is a tropical and subtropical species, else it would probably have been picked up in some of the many deep towings that have been made farther north and east in the Atlantic.

Vertical Range: All the records for *H. valdiviae* have so far been from hauls that worked down to at least 500 meters; in most cases to at least 1,000 meters. Its bathypelagic status thus seems established.

More precise information as to the depth of its chief center of abundance would be of interest, because, while colorless, most of the captures, like those of *Halicreas minimum,* have been in nets working so deep as to indicate that the specimens were from levels inhabited also by the deeply pigmented groups of medusae, and by the black bathypelagic fishes.

GERYONIDAE.

Liriope.

Although this sharply defined genus is perhaps the most often encountered of Trachomedusae, there has been no agreement as to the specific relationships of its many described representatives, owing to the difficulty (I believe we may say "impossibility") of finding any differences, the gaps between which cannot be bridged by examination of sufficiently large series. Final decision that all known representatives of *Liriope* represent but a single variable species was already foreshadowed in Browne's (1927) interesting exposition of the situation that faces every student of the genus. Thiel (1936, p. 45) has now definitely made this union of all the named forms under the oldest designation, *L. tetraphylla* Chamisso and Eysenhardt. And the reader is referred to his discussion for a clear exposition of the reasons justifying this procedure. Granting, however, that the various forms of *Liriope* cannot be considered "species," in the sense in which the term is generally employed in zoological nomenclature, it still remains an interesting question how they are to be interpreted, and how recorded in scientific literature. While it is now established that intergrades can be found with regard to every character which has been suggested as specific, we have still to recognize that the representatives of different swarms, or of different populations (seasonal or regional), often do differ so widely in many respects, as Browne (1927) has vividly described, that they would be referred without hesitation to different species had not the existence of intermediates been proved.

Liriope tetraphylla Chamisso and Eysenhardt.

Geryonia tetraphylla, Chamisso and Eysenhardt, 1821, p. 357, Pl. 27, Fig. 2.

For lists of references to the named forms of *Liriope,* all of which, following Thiel (1936) are now referred to *L. tetraphylla,* see Mayer, 1910, p. 413-424; also, Thiel, 1936, p. 45.

Material: Net No. 51, Surface, April 29, 1929, 1 specimen about 5 mm. in diameter.

The gonads in this young specimen are of about the same form as in a 7 mm. specimen, already pictured from the eastern tropical Pacific (Bigelow, 1909, Pl. 4, Fig. 3), namely, squarish with rounded angles. This stage has already been proved preliminary to the triangular or rhomboid outlines often, but not always, attained by adult *L. tetraphylla.*

The most interesting thing about this record is that 974 hauls in various months from May to October, in two different years, yielded only the one specimen of a genus so widespread and frequently abundant in warm seas. Nor can the paucity be credited to the depths at which the hauls were made, for 108 of them were in the upper 200 meters; 86 right at the surface. This, added to the corresponding fact that the *Bache* hauls in the winter of 1914, yielded only 4 *Liriope* at 2 stations on lines run between Cape Hatteras, Bermuda, the Bahamas, and the Straits of Florida, can only mean that it was decidedly rare in this side of the Sargasso Sea area during the periods in question, which included both the warm and the cold months. This is the more astonishing, when one remembers that the Plankton Expedition (Maas, 1893) took *Liriope* regularly from Latitude about 40° N., southward to Bermuda; and thence eastward all along the track across the tropical Atlantic.

Geryonia.

Geryonia proboscidalis Forskål.

Medusa proboscidalis, Forskål, 1775, p. 108.

For synonymy, see Bigelow, 1909, p. 116, and Mayer, 1910, p. 425.

Material: Net No. 613, 1,097-0 meters, 1 fragmentary specimen, diameter about 30 mm.

Net No. 621, 1,097-0 meters, 1 fragmentary specimen, diameter about 16 mm.

Net No. 850, 1,463-0 meters, 1 fragmentary specimen, diameter about, 25 mm.

These very fragmentary specimens (identified by the number of canals) add nothing to previous knowledge of the morphology of this well known species.

Geryonia had already been reported to the north and to the east of Bermuda (Maas, 1893) as well as at many other localities in the warm belt of the Atlantic.

NARCOMEDUSAE.

In the classification adopted by Broch (1929), by Ranson (1936), by Uchida (1928), and by me in earlier papers (Bigelow, 1909; 1913; 1918; 1919), the Narcomedusae that have gastric pockets are divided into two families, Cuninidae and Aeginidae, depending on whether the pockets are perradial, equal in number to the tentacles, and not extending out beyond the points of origin of the latter (Cuninidae), or whether the definitive pockets are interradial in location, and at least twice as numerous as the tentacles, with the tentacles arising in the notches between the pockets (Aeginidae). This scheme is followed here. Thiel (1936, p. 55), on the contrary, follows Mayer (1910), in referring all Narcomedusae with peripheral gastric pockets to one family, Aeginidae.

Such of the typical Narcomedusae as lack gastric pockets are now generally grouped in the family Solmaridae. If the curious sand-dwelling form, *Halammohydra*, actually is an aberrant Narcomedusa, as Remane (1927), Uchida (1928), and Leloup (1935) believe, it calls for a separate family (Halammohydriidae, Remane).

Cunina.

Cunina sp.?

Material: Net No. 242, 1,646-0 meters, 1 specimen, about 30 mm. in diameter.

Although this specimen is very much damaged, enough remains to show that it had perradial gastric pockets, and a well developed peronial canal system, a combination of characters locating it in the genus *Cunina*, as contrasted with *Solmissus*, which lacks canals. Unfortunately, the exumbrella is so much rubbed or macerated, that it is impossible to tell whether, or not, otoporpae were present. And all the otocysts have been destroyed. There are 23 large tentacles and one very small one. Identification of any specimen of *Cunina* with as many as 20 tentacles depends, in the first place, on decision whether the *Medusa mucilaginosa* of Chamisso and Eysenhardt (1821), with 21-24 tentacles, belonged to *Cunina*, to which Blainville (1834) referred it, or whether it actually was a *Solmissus* according to the definitions for these two genera now generally adopted. The name *mucilaginosa* was used by Vanhöffen (1908a, as "*Solmaris mucilaginosa*") for a series of Cuninidae of large size (25-60 mm. in diameter), with 21-24 tentacles. But since his specimens lacked peronial canals (he gave no information as to the presence or absence of otoporpae), they are more likely to have belonged to *Solmissus* than to *Cunina*.[12] And I have argued (Bigelow, 1909, p. 55; 1918, p. 392) that it was wisest to discard *mucilaginosa* as a nomen nudem, because it will never be possible to tell from Chamisso and Eysenhardt's account, to which of these two genera their original specimens did actually belong, lacking information on the critical points—canals and otoporpae. Ranson (1936, p. 200), however, has recently revived this name, for a *Cunina* of 55 mm. with 21 tentacles.

---

[12] See Bigelow, 1919, p. 327, for discussion of Vanhöffen's treatment of the genus *Solmissus*.

Without attempting to settle this question, I may point out that if *mucilaginosa* be finally accepted as a *Cunina*, it was the earliest named member of this genus. Hence, if it lies within the varietal range of the species commonly called *rubiginosa*, a possibility suggested by Thiel (1936), *mucilaginosa* must take precedence over *rubiginosa*, and the latter becomes a synonym of it.

Solmissus.

? **Solmissus incisa** Fewkes.

Solmissus incisa, Fewkes, 1886, p. 954, Pl. 9; Bigelow, 1909, p. 67, Pl. 21, Figs. 1-3, 5; 1913, p. 57; Mayer, 1910, p. 483; Broch, 1929, p. 527; Uchida, 1928, p. 90; Bigelow and Leslie, 1930, p. 560; Ranson, 1936, p. 206.

Solmissus faberi, Haeckel, 1879, p. 350.

Solmissus bleekii, Haeckel, 1879, p. 351.

? *Solmaris rhodoloma*, Vanhöffen, 1908a, p. 60, Pl. 1, Fig. 5. [non *Aequorea rhodoloma* Brandt, 1838.]

Material: Net Nos. 599, 628, 632, 680, 700, 713, 735, 753, 765, 799, 848 885, 891; 914-0 to 1,829-0 meters; 13 specimens; those of which measurement is possible, range from about 50 mm. to about 75 mm. in diameter; also other fragments.

These specimens — all extremely fragmentary — are identifiable as *Solmissus* because they show indications of the presence of gastric pockets in the radii of the tentacles, but no signs of a canal system. In all cases, the free gastric wall has been destroyed, but persistant bands of subumbral tissue, around the outer margins of the pockets, and in the septal spaces between them, show the pockets to have been oval in outline and somewhat longer than broad. This fact, combined with the large number of tentacles (see below), warrant tentative reference to *S. incisa*. And this identification is rendered the more probable by the fact that even in their present state, they agree in thinness of the disc, in softness of the gelatinous substance, and generally in appearance, with the *incisa* collected by the *Albatross* in the Pacific, with which I have been able to compare them.

In no case was an exact count of the tentacles possible, but the presence of at least 23 in one specimen of about 55 mm., and of 25 to 30, in three others of, roughly, 60 and 75 mm., corresponds with earlier counts, which have shown a range of from 23-40 in specimens 50 mm. in diameter or larger. This contrasts with a maximum of 16 tentacles in *S. albescens* and in *S. marshalli.*

All specimens of *S. incisa* previously seen have lost all trace of the gonads, nor is the present series any better in this respect. They do, however, confirm Fewkes' original illustration of the marginal outline as straight or nearly so, from peronium to peronium. All the otocysts have been lost, and even the pads on which these organs stand.

General Distribution: *S. incisa* was to be expected in the vicinity of Bermuda, for it has been taken at several stations along the American continental slope, between the latitudes of Cape Hatteras and of Sable Island, Nova Scotia, on the one side, and mid-way between Bermuda and the Azores on the other. Other Atlantic records are off the coasts of France and of Spain. It has also been taken at a number of localities in the eastern tropical Pacific; off Monterey, California; between San Francisco and the Aleutians; in the Bering Sea region; off Kamchatka; and in Japanese waters.

Vertical Range: Most of the captures of this species have been from hauls made with open nets at considerable depths, but the list includes three captures from the surface, one from the northwestern Atlantic (Fewkes, 1886), the others from the eastern tropical Pacific (Bigelow, 1909).

AEGINIDAE.

Aegina.

Up to 1910, fourteen supposed "species" referable to *Aegina* had been described. Mayer's (1910) summary made it clear, however, that this list required drastic reduction. And as the result of subsequent studies, by various authors, evidence has gradually accumulated to the effect that all Aeginas yet described represent at most two species, the *Ae. rosea* and *Ae. citrea* of Eschscholtz (Bigelow, 1913; 1919; Broch, 1929; Ranson, 1936); or perhaps only one as Thiel (1936) has most recently argued. Decision here rests on whether the difference between the "*citrea*" type, in which the margin of each of the eight adradial gastric pockets is more or less indented in the mid-line, and the "*rosea*" type in which it is entire, is genetic, or is simply the result of sex or of age differences, of differing degrees of distention of the pockets, or of contraction, as Thiel (1936) maintains. The situation may be summarized as follows (see Thiel, 1936, p. 74, for details): Juveniles, up to perhaps 9 mm. in diameter, have undivided pockets, i. e., are, as a rule, of the "*rosea*" type; all very large specimens (35 mm. in diameter or larger), so far recorded, (of which adequate descriptions were given) have likewise been of the "*rosea*" type;[13] for example, Haeckel's (1879) *Ae. rhodina*, and the *rosea* reported by me (1913) from the northwest Pacific. Among middle-sized individuals, however, of, say, 9-25 mm. in diameter, both types have been recorded. Otherwise stated, all typical *citrea* have fallen within this size range, whereas the much more numerous records of the *rosea* type have covered the entire size range so far recorded for the genus. Furthermore, several specimens of 7-16 mm. in the present series show intermediate conditions, with some of the adradial pockets notched, others not, or showing a slightly sinous outline. One point not previously stressed is that in specimens of the *citrea* type the gonads usually (but not always) form two swellings on the oral surface of each primarily adradial pocket, whereas in the *rosea* type, the swelling involves the oral surface of each of the 8 pockets as a whole. In oral view, that is to say, there are up to 16 very conspicuous swollen areas (sometimes only 14 or 15) in the *citrea* type, but only 8 in the *rosea* type. And this difference is much more conspicuous than is the difference in outline of the pockets, for even at its maximum, the latter is slight.

The question as to the relationship of the two types cannot be settled until a microscopic study is made to determine whether we may not be dealing here with a sexual dimorphism—nor would this be unique among Narcomedusae, for the gonads of the two sexes of *Aeginura* differ widely, in appearance. But the present series does not offer hopeful material for histological study. It is also possible that the very large representatives of the *rosea* type are spent individuals. Nor can the rôle played in this matter by contraction be determined without a study of living material.

Meantime it seems wisest to follow Thiel, at least provisionally, and to class *citrea* and *rosea* as forms (of undetermined significance) of one species. This, however, must be named *citrea*, not *rosea* as Thiel has called it, because the former has page priority in Eschscholtz's (1829) original accounts of the two.

---

[13] *Ae. alternans* (Bigelow, 1909) was probably a large damaged *rosea* (Bigelow, 1913, p. 59).

Aegina citrea Eschscholtz.

Aegina citrea, Eschscholtz, 1829, p. 113, Pl. 10, Fig. 3.

It is probable, as explained above, that all the citations to supposed species of *Aegina*, listed by Mayer, 1910, p. 451-454, refer to one variety or another of this species. For a recent list of references, see Thiel, 1936, p. 73 ("*Ae. rosea*").

Material: Net Nos. 263, 292, 294, 296, 488, 564, 566, 576, 627, 649, 657, 666, 686, 692, 693, 708, 745, 762, 779, 800, 809, 857, 874, 882, 885, 971; hauls from 0 to 1,829-0 meters; 31 specimens, 5-20 mm. in diameter, in various stages of preservation.

Among the specimens that are well enough preserved to show the gastric pockets, 9 (ranging in diameter from 5-20 mm.) are definitely of the *rosea* type, i.e., the adradial pockets show no signs of additional subdivision. Two, of 15-16 mm., are as definitely of the *citrea* type. The most interesting specimens are nine others (7-16 mm. in diameter) which show various intermediate states as follows:

A. Each adradial pocket shows but one swelling ("*rosea*" type); margins of some pockets entire ("*rosea*" type), of others notched ("*citrea*" type).

B. Some pockets show "*citrea*" swellings, some "*rosea*"; margins of all pockets entire ("*rosea*" type).

C. Swellings as above; margins of some pockets notched ("*citrea*" type), of others entire ("*rosea*" type).

D. Each pocket with 2 swellings ("*citrea*"); but with margin entire ("*rosea*").

Obviously, these corroborate Thiel's (1936) view that it is not possible to segregate two groups (however named) on this basis. However, we are still faced with the fact that while a great majority of specimens of the "*citrea*" type show the normal metamerism, a large proportion of those of the "*rosea*" type that have been seen, have had 5 or more tentacles. This was, indeed, the case with Eschscholtz's original series of *rosea* (4 specimens, 3 with 5 tentacles, one with 6 tentacles), and has repeatedly been reported since; see especially Vanhöffen (1908a) and Uchida (1928). The present series again yields 3 pentamerous specimens among the 9 of *rosea* type just mentioned, the others having 4 tentacles each. A possible explanation is that variants of this sort are more frequent in one sex than in the other.

Reduction of the tentacles also occurs, though more rarely; the series includes one specimen of 9 mm. with only three tentacles. But it is too much contracted to allow classification, as to type.

While most authors who have written of *Aegina* have described it as having only a small number of otocysts, Vanhöffen (1908a) found about 20 per marginal sector in one of the "*rosea*" type, 16 in one of the "*citrea*" type. And while I have not been able to make a complete count of otocysts, even for a single sector, of any of the Bermuda specimens, the spacing of such of these organs as are still recognizable, or of their basal pads, is consonant with Vanhöffen's counts.

General Distribution: *Aegina citrea* is widespread in the warm belts of all oceans—this was already known to apply both to the *citrea* and *rosea* forms—also in the Mediterranean. Southward, it had been taken in the sub-Antarctic; and northward to the Bering Sea region in the Pacific; to Lat. 58° N. in the northeastern Atlantic. The present series is, however, interesting geographically because there was no previous record of *Aegina* in the western half of the north Atlantic except close to the coast (see Thiel, 1936, p. 76, Fig. 15, for a recent chart of this distribution).

Vertical Range: *Ae. citrea* has repeatedly been taken at the surface (the Bermuda series includes 2 surface hauls), but also in open nets lowered to various levels, and—more instructive—in closing nets from 1,000-700 meters (Vanhöffen, 1908a, as "*Ae. lactea*"); about 800 meters (Bigelow, 1909); 200-100, 600-400, 700-500, 800-600, and 1,030-830 meters (Thiel, 1936, "*Ae. rosea*"). Its bathic range is thus very wide.

Thiel (1935, p. 81) has also pointed out that the specimens taken deepest averaged the largest, those taken shoalest, the smallest; evidence that *Aegina*, like various other medusae, reproduces chiefly near the surface, tending to sink, with increasing age. This is corroborated by the Bermudian collection, the distribution of catches with depth being:

Depth in Meters.	Number of Specimens.
0	2
914-0	2
1,097-0	3
1,280-0	4
1,463-0	11
1,646-0	5
1,827-0	4

Aeginura.

It is now generally agreed that all representatives of *Aeginura* that have been examined recently, are referable to the wide-ranging, bathypelagic species, named *Ae. grimaldii* by Maas (1904) from the collections of the Prince of Monaco. Thiel (1936), in his historical survey of the genus, goes still further, in definitely uniting *grimaldii*, and its more recent synonyms, with the *Aeginura myosura, Cunoctona nausithoe*, and *C. lanzerotae* of Haeckel (1879); hence he employs the latter name (it has page priority over *nausithoe* and *myosura*). This point is discussed in an earlier publication (Bigelow, 1913, p. 60). I need only repeat here, that (quite apart from the presence or absence of a peronial canal system), if we are to conclude that the *Aeginura* of modern students is identical with these older Haeckelian species we must assume (a) that the otoporpae so clearly shown in Haeckel's (1879, Pl. 20, Figs. 1-2) illustrations of his two species of "*Cunoctona*" were imaginary; and (b) that the absence of secondary tentacles and the small number of otocysts (16 indicated) in his *Ae. myosura* were the result of mutilation. As his descriptions were based on preserved (no doubt alcoholic) material, the second assumption is not unreasonable. But there is no way to establish the correctness of either of these assumptions; and it is possible that an *Aeginura* lacking secondary tentacles and with very few otocysts, may some day be found. It, therefore, seems to me wiser to treat Haeckel's old names as doubtful synonyms of *grimaldii*, rather than to select one of them as the name for the species in question.

I need only note farther that if Haeckel's accounts were to be taken at face value, *grimaldii* could not be referred to his genus *Aeginura* at all, because he described the latter as having a well-developed canal system. But as Maas (1905, p. 78) pointed out, what Haeckel (1881, Pl. 13, Fig. 7) pictured as canals were in reality parts of the gastric pouches.

Aeginura grimaldii Maas.

Aeginura grimaldii, Maas, 1904, p. 38, Pl. 3, Figs. 19-28; Bigelow, 1909, p. 80, Pl. 9, Fig. 4; 1913, p. 61; Mayer, 1910, p. 470; Kramp, 1913,

p. 276; 1914, p. 436; 1920, p. 6; 1924, p. 37; Broch, 1929, p. 533, Fig. 37; Thiel, 1932a, p. 156; Ranson, 1936, p. 211.

Aeginura weberi, Maas, 1905, p. 77, Pl. 11, Fig. 73, Pl. 12, Fig. 76, Pl. 14, Figs. 90-99.

Cunoctona grimaldi var *munda*, Vanhöffen, 1908a, p. 53, Pl. 2, Fig. 6.

Cunoctona guinensis, Vanhöffen, 1908a, p. 53, Pl. 3, Fig. 29.

Cunoctona obscura, Vanhöffen, 1908a, p. 52, Pl. 2, Fig. 7, Pl. 3, Figs. 25-28, 30.

Aeginura lanzerotae, Thiel, 1936, p. 86.

? *Aeginura myosura*, Haeckel, 1879, p. 343, Pl. 19, Figs. 8-9; 1881, p. 41, Pl. 13-14; Mayer, 1910, p. 468.

? *Cunoctona lanzerotae*, Haeckel, 1879, p. 318, Pl. 20, Figs. 1-6.

? *Cunoctona nausithoe*, Haeckel, 1879, p. 318.

? *Aeginura lanzerotae*, Mayer, 1910, p. 469.

Material: Net Nos. 18, 22, 24, 36, 41, 48, 49, 52, 53, 64, 66, 67, 69, 73, 78, 111, 121, 122, 137, 270, 293, 295, 362, 400, 427, 442, 455, 468, 481, 539 562, 582, 605, 606, 612, 620, 621, 627, 628, 631, 632, 635, 638, 639, 645, 646, 652, 654, 665, 680, 681, 685, 698, 700, 702, 708, 712, 715, 719, 720, 721, 724, 726, 732, 740, 742, 745, 746, 753, 759, 760, 761, 778, 779, 781, 793, 794, 804, 805, 810, 811, 812, 842, 849, 852, 861, 885, 894, 959; hauls from 540-0 to 1,829-0 meters; 184 specimens, 1-6 per haul. Also, Net Nos. 26, 42, 65, 76, 110, 143, 295, 360, 447, 488, 598, 716, 929, 949; 19 specimens, probably belonging here, but so fragmentary as to preclude positive identification.

In spite of its extent, the collection adds nothing to previous knowledge of the morphology of this species, for the specimens are all in such poor condition that it is only the very characteristic appearance of *Aeginura*—especially the large tentacle roots, the outlines of gastric pockets, and the dense pigmentation—that makes them recognizable at all. It was disappointing that the margins are in every case so battered that neither the secondary tentacles peculiar to the genus, nor the otocysts, are to be seen. The very large white eggs are, however, so resistant that they are still visible in specimens from Net Nos. 111, 122, 468, 606, 726, 761, 794, 810, and 959. These catches were made in the months of May, June, July, August, and September, evidence that in this region the breeding season of *Aeginura* covers spring, summer, and early autumn—very likely the entire year.

General Distribution: The wide distribution of previous records (Thiel, 1936, Fig. 18) had already established the cosmopolitan nature of this medusa in the ocean basins. The present captures are, however, interesting as the first for the eastern side of the North Atlantic; interesting also as showing that this is one of the most regularly occurring medusae at suitable depths in the Bermuda region, which may be taken as representative of the Sargasso Sea as a whole.

Vertical Range: Up to the present, there is no positive evidence that any *Aeginura* larger than 8-10 mm. has been taken from a depth less than 400-500 meters, for while the great majority of captures have been in open nets, those taking adults have in every case sampled the water down to at least this depth—in most cases much deeper. And there is record of closing net captures of adults from about 780 meters (Maas, 1904), as well as from 1,000-700 meters and deeper (Thiel, 1935, Table 16). Thus, when adult, *Aeginura* belongs to the same bathypelagic community as *Atolla* and *Periphylla*, as indeed, its dense pigmentation would indicate. The depth distribution of the Bermuda hauls yielding *Aeginura*, relative to the total number made at each depth, tabulated below, suggests a rather definite concentration between, say, 1,000 and 1,600 meters.

Depth in Meters.	Total Number Hauls.	Number Hauls with *Aeginura.*	% with *Aeginura.*
549-0	23	1	4
732-0	40	2	5
914-0	132	9	7
1,097-0	134	19	13
1,280-0	132	27	19
1,463-0	132	19	14
1,646-0	135	17	13
1,829-0	135	8	6
2,012-0	4	0	0

Thiel (1935), however, has recently made the interesting discovery that young stages of 1-5 mm. occur in the upper water layers, the *Meteor* having taken them on four occasions shoaler than 100 meters, once shoaler than 50 meters (Thiel, 1936, p. 86). From this, he suggests that the eggs rise to the surface, and that, as growth proceeds, the young medusae sink deeper and deeper, as seems commonly to be the case among bathyplanktonic animals.

SOLMARIDAE.

Pegantha.

? Pegantha clara R. P. Bigelow.

Pegantha clara, R. P. Bigelow, 1909, p. 80; Mayer, 1910, p. 445; H. B. Bigelow, 1918, p. 397.

Polycolpa forskali, Vanhöffen, 1908a, p. 56; 1912, p. 391; 1912a, p. 32. [Non *P. forskalii* Haeckel, 1879; 1881.]

Pegantha smaragdina, H. B. Bigelow, 1909, p. 90, Pl. 14, Fig. 1, 2, Pl. 19, Figs. 1-9, Pl. 22-26.

Material: Net Nos. 50, 157, 271, 720, 812, 882, 902, 959; 914-0 to 1,463-0 meters; 8 fragmentary specimens, about 10-about 20 mm. in diameter.

Although damaged, having lost all trace of exumbral sculpture, and with the stomach much battered, the specimens all show the peronial canals, and the outlines of the stomach without any trace of gastric pockets, that are characteristic of *Pegantha.* Owing to the obvious contraction of some specimens and the flattening of others, it is not possible to state the normal relationship of heighth to breadth: in the present state they suggest that at diameters of 10-20 mm., the bell of this species is from ¼ to ½ as high as broad; perhaps still higher relatively in some cases.

The tentacles range in number from about 20 to about 24; the largest number being in a specimen of about 12 mm., while the largest specimen has only 22 tentacles. The small specimens (6 in number, 10-12 mm. in diameter) without gonads, are referred to this species chiefly because this is the only *Pegantha,* yet known, in which upwards of 18 tentacles have been found before the development of the gonads. This identification is strengthened, in the case of the 20 mm. specimen, by the fact that traces are to be seen of simple interradial swellings—forerunners of the gonads—at the margin of the stomach.

Most of the otocysts have been lost; but the spacing of those still visible suggests the presence of 3-5 per marginal lappet; or about the number to be expected in juveniles of *P. clara,* in adults of which there may be up to 8 per lappet. In only one specimen are traces of the otoporpae still to be seen.

General Distribution: The original record of *P. clara* was from the continental slope in the offing of Woods Hole, and young specimens were taken near the Bahamas by the *Bache* (Bigelow, H. B., 1918), so that it was to be expected at Bermuda. Other records referable to it are from the vicinity of the Cape Verde Islands (Vanhöffen, 1912, *"Polycolpa forskali"*), off Chile (Vanhöffen, 1912a, *"Polycolpa forskali"*), off Peru, (Bigelow, 1909, *"Pegantha smaragdina"*), and from the tropical Pacific between Hawaiian and Caroline Islands (Vanhöffen, 1912a, *"Polycolpa forskali"*).

Vertical Range: Previous records include both the surface, and open net-hauls from considerable depths.

SCYPHOMEDUSAE.

Carybdeida.

Mayer (1910) grouped all known Carybdeida in a single family—Carybdeidae. For convenience, however,—even if for no other reason—it seems preferable to follow Krumbach (1925) and Uchida (1929) in limiting that family to forms which lack gastric pouches projecting from the manubrium into the subumbrella cavity, and in which there are only 8 (adradial) marginal pockets. The more complexly organized forms with free gastric pouches and more numerous (16) marginal pockets are divided by Krumbach (1925) into 2 families, but (I believe more logically) grouped by Uchida in one, Chirodropidae. The latter need not be discussed here, as it is not represented in the Bermuda collection.

CARYBDEIDAE.

Few pelagic coelenterates came to scientific attention earlier than did the quadritentaculate members of this family, for the well known Mediterranean *Carybdea* was described by Linnaeus, (1758). Since that time, the number of named forms multiplied, until Mayer (1910) gave a list of twenty-one. It was already obvious, however, that the number of actual species represented was much smaller. And although insufficiency of most of the early descriptions precluded revision, Mayer (1910) tentatively classed all of them as varieties of four species at most. The carybdeids have subsequently been the subject of repeated discussion, notably by Stiasny (1919, 1926, 1929, 1930, 1934, 1935, 1937), by Uchida (1929), by Thiel (1928) and by Menon (1930). But views held, as to generic and specific characters, have been so divergent that a résumé is requisite, before the Bermudian specimens can be discussed even though these belong to forms known for many years.

Much of the confusion has resulted from uncertainty as to how much weight should be given (in classification) to the position of the groups of gastric filaments (phacellae); i. e., whether in clusters or horizontal bands at the 4 interradial corners of the stomach (*Carybdea* type), or extending as vertical bands along the interradial sides of the latter, as described by Müller (1858), for *Tamoya haplonema*. Unfortunately, Müller's illustration did not show the location of the filaments. And while his account of their location has repeatedly been quoted, or paraphrased, no first-hand description of this type of phacella appeared subsequently until Stiasny (1919, p. 40) found the phacellae forming "interradiale vertikale Fadenreihen längs der Magenseiten," in Sumatran specimens otherwise agreeing so closely with Müller's *Tamoya* that generic identity was assured. And in 1934 Stiasny (1934) was at last in the position to present a good illustration of a West African carybdeid, evidently referable to Müller's *T. haplonema*, clearly showing this same vertical arrangement, with phacellae extending along ⅔ of the length of the stomach. It is thus proved that the type species of *Tamoya* differs from the type of *Carybdea* (*C. marsupialis*, Linné) not only in the larger stomach and in the presence of mesenteries (often used as the chief generic separation), but equally sharply in the arrangement of the phacellae.

Uchida (1929, p. 175), it is true, described the phacellae as "numerous short gastral filaments in the interradial crescentic area of the stomach," for a Japanese carybdeid agreeing otherwise with *Tamoya* (i.e., in the structure of the stomach, mesenteries, and canalization), hence, no doubt correctly, referred by him to that genus. But he did not illustrate the phacellae. And Stiasny (1930, p. 10) included their arrangement as one of the alternative characters for the genera, *Tamoya* and *Carybdea*, a course followed here, as well.

On the other hand, it proves necessary to abandon size and the prominence of the exumbrella sculpture, as generic characters—also included by Stiasny in his recent synopsis—because the Bermudian collection (p. 144) verifies Agassiz and Mayer's (1902) account of the existence of at least one species with the *Carybdea* type of stomach (i.e., flat and lacking mesenteries) and phacellae, but with weak sculpture and growing to a larger size than any other carybdeid yet seen. Thus, if the generic separation is to be based primarily on structural features—and that this is the more logical procedure need hardly be defended—we arrive at the following:

1. Stomach flat, without mesenteries: gastric cirri forming brush-like bundles at the interradial corners of the stomach, or (if expanded) crescentic areas extending horizontally.................................*Carybdea.*
2. Stomach deep, connected with the subumbrella by well developed perradial mesenteries: gastric cirri in bands, extending vertically along the walls of the stomach, in the interradii...............................*Tamoya.*

This, the reader will observe, is a return to the scheme long ago proposed by Haeckel (1880); an instance where the latter's classic system has proved more prophetic of knowledge to come than it was justified by facts at hand at the time.

The family, Carybdeidae (as here defined), also includes one well known genus, *Tripedalia,* which shows a multiplication of tentacles, but otherwise resembles *Carybdea* and *Tamoya* in simplicity of organization.[14]

Carybdea.

Among the Carybdeas that have yet come to light, one, recently described by Stiasny (1930), but unnamed, is set apart by the fact that its tentacles bear lateral branches. As the tentacles in all other members of the family—whether single or grouped—are simple, this form certainly deserves specific recognition. The new species, *Carybdea stiasnyi,* is therefore proposed for it. Stiasny (1930, p. 5) suggests that "auf Grund dieses einen Merkmals könnte ein neues Genus aufgestellt werden." But in this regard, we may well await the action of its discoverer.

Successive studies by different authors have brought cumulative evidence to support Mayer's (1910) contention that all other named forms of *Carybdea* in reality represent nothing more than varieties or races of a very small number of good species. But views have differed as to how many such deserve recognition, largely because of the uncertainty as to which, if any, of the supposed "Carybdeas," should actually be referred to its companion genus, *Tamoya.* A survey of recent literature, added to the specimens I have myself seen, corroborates Mayer's (1910) view that the great majority of Carybdeas, the generic identity of which is established by adequate description or by illustration of the critical characters, fall in one or other of the following well differentiated groups:

---

[14] Haeckel's (1879-80) problematical genera *Procharagma* (lacking velum) and *Procharybdis* (with velarium, but lacking velar canals) would also fall among the Carybdeidae, should it ever prove that any existing carybdeids show these primitive states when adult, i. e., that they were not founded either on multilated specimens, or on juvenile stages.

Group A. Of small or moderate size (for the most part less than 50 mm. high); with strong exumbral sculpture; with the gastric cirri in each cluster arising either from a single basal stalk or from stalks closely clustered at the four interradial corners of the base of the manubrium. The earliest named *Carybdea, C. marsupialis* Linné, of the Mediterranean, was of this type; so also two other well known forms, *C. xaymacana* Conant from the West Indian region, and *C. rastonii* Haacke of the Indo-Pacific—likewise *C. murrayana* Haeckel, from West Africa.

Mayer (1910, p. 508) in his tabular view classes *xaymacana* as a variety of *marsupialis* from which it differs only in somewhat smaller size, in having fewer and less complexly branched velar canals (4 per quadrant instead of up to 6 or 8), and phacellae arising from a single primary trunk, instead of from 8-10 primary branches.

The unity between *xaymacana* and *marsupialis* with respect to the phacellae is in fact, even closer than Mayer supposed. On the one hand, Claus (1878) long ago pointed out that in *marsupialis* each group of filaments arises from a single main trunk, while on the other, my own examination of Bermudian and Bahaman specimens of *xaymacana* described below (p. 139) shows that the basal trunk divides into several primary branches, each of which bears a cluster of filaments either simple, or showing further dendritic branching (Text-figs. 3, 4, 5), much as described for *marsupialis.* Nor are there any differences in the outline of gonads and of pedalia, in the shape of the rhopalar nitches, or in exumbral sculpture, that can not be explained as due to contraction, or—at most—to individual variation.

Comparison does, however, substantiate the supposed difference in canalization, for whereas in the *xaymacana* that I have seen, as well as in those described by Conant (1898), by Mayer (1910), and by Stiasny (1919), there have been at most four (sometimes three, according to Stiasny), unbranched or simply forked canals per quadrant, there may be 6 or even 8 in *marsupialis,* some of them complexly subdivided. In canalization, then, *xaymacana* corresponds to half-grown *marsupialis;* as it does in the fact that the largest so far seen (with large gonads) have been only ½ to ⅔ as high as mature *marsupialis.*

Present indications, therefore, are that *xaymacana* is a dwarf—perhaps paedogenetic—form of *marsupialis;* one, too, with a different geographic distribution, for the typical (*marsupialis*) form has never been seen in the western side of the Atlantic, nor the dwarf (*xaymacana*) form in the eastern. Furthermore, *C. murrayana* bears much the same relationship to *marsupialis* that the latter does to *xaymacana,* for while it agrees with *marsupialis* in sculpture and in the structure of its phacellae, its velar canals are not only more complexly branched than in typical *marsupialis,* but more numerous, i.e., 10-12 per quadrant. It is, indeed, doubtful whether a half-grown *murrayana* would be distinguishable from a full-grown *marsupialis*—except perhaps, by the state of development of the gonads—or a half-grown *marsupialis* from a fully-grown *xaymacana,* though there would be no danger of confusing full-grown specimens.

Forms bearing a relationship of this sort, one to the other, would unhesitatingly be named "subspecies" by students of molluscs, of crustacea, or of the higher vertebrates. And as they certainly require recognition in nomenclature, more precise than the vague designation "variety," it seems justifiable to introduce trinomials into the classification of pelagic coelenterates, also, to cover such cases.

The discussion must also touch on the status of *C. rastonii,* because if the latter be, in fact, indistinguishable from *xaymacana,* as Stiasny (1919) has suggested, the combined subspecies must be named *rastonii* Haacke

(1886), this being the older of the two names; or perhaps even *prototypus* or *cuboides*, if it finally prove that Haeckel's (1880) problematical *Procharagma prototypus* and *Procharybdis cuboides* are young *rastonii* as Mayer (1910, p. 509) has classed them.

Apart from geographic distribution, the only distinctions between *xaymacana* and *rastonii*, listed in Mayer's (1910) tabular view, are slight differences in shape and relative length of pedalia, and in length of tentacles, which certainly would not justify separation. Furthermore, the canalization of *rastonii* is intermediate, in type, between that of typical *marsupialis*, and of the subspecies, *xaymacana*.

On the other hand, *rastonii* does differ from *xaymacana* in the structure of its phacellae, for, whereas in *xaymacana* all, or most of the primary branches arise from a single basal trunk (p. 140), in *rastonii* they arise independently from the gastric wall, in a row, flanked on either side by several simple cirri, as long ago described by Haacke (1887, Pl. 35, Fig. 4), a state derived (in young medusae) from a row of simple cirri.[15] And this difference, by which specimens of *rastonii* can be recognized at any stage after the appearance of the gastric cirri, seems sufficient to warrant its continued recognition as a distinct species, to emphasize the fact that the Indo-Pacific representative of this group differs more widely from the Atlantic representatives, than do the latter, one from another.

Group B. This group includes much larger forms up to 230 mm. high; relatively narrower in outline than the *marsupialis* group; with weak exumbral sculpture, if any; with the gastric cirri grouped along crescent-shaped rows centering at the interradial corners of the base of the gastric cavity. Recent collections have repeatedly yielded large *Carybdea* of this type, most frequently reported as *C. alata* Reynaud, as *C. grandis* Agassiz and Mayer, as *C. moseri* Mayer, or as one or other of the last two considered as a variety of the first. According to various accounts the group differs also from the *marsupialis* group, in the form of the pedalia, in the relative heighth of the rhopalia above the bell margin; in the outline of the rhopalar nitches, and in the more numerous velar canals, as described below (p. 146, 147).

The earliest named form that can be positively referred to this group (because of the distinctive characters of bell and of phacellae) was *C. grandis* Agassiz and Mayer (1902) from the tropical Pacific, half-grown individuals (or a dwarf race) of which were redescribed shortly afterward by Mayer (1906) as *C. moseri*. But it seems probable that *C. alata* Reynaud (1830) was based on a young *Carybdea* of this same type, for the original illustration shows a rounded, non-sculptured bell, nor is there anything in Reynaud's illustration or account to argue to the contrary. Consequently, Vanhöffen (1908) revived the name *alata*, for Carybdeas from the Indian Ocean and Straits of Malacca, that agreed with *grandis* in canalization and in structure of phacellae. Mayer in his tabular view (1910, p. 508), followed Vanhöffen in classifying both *grandis* and *moseri* as varieties of *alata* Reynaud, as have subsequent authors, generally.[16] And while one must admit that it will never be possible to determine, with absolute certainty, the identity of the specimen pictured by Reynaud, because no description was given of the morphological features on which identification primarily depends, to follow Vanhöffen will tend toward stability of nomenclature. The situation is, however, confused by the fact that Uchida (1929), while agreeing that *grandis* and *moseri* belong in the synonymy of *alata* Reynaud, transferred the latter name to a species of *Tamoya*, on the supposition that Agassiz and Mayer's (1902) original figures of *grandis* referred to a member of that genus, not to a *Carybdea*. And this course has been followed by Stiasny (1929;

---

[15] I have been able to confirm Haacke's (1887) account of stages in development for small and middle-sized specimens from the tropical Pacific (Bigelow, 1909), and for a large series from Japan, in the collection of the Museum of Comparative Zoology.

[16] Thiel (1928) has revived the name *grandis*.

1930, 1935, 1937), likewise by Rao (1931). Successive examinations of specimens of the *alata-grandis* type have, however, proved that actually they have the shallow stomach and the arrangement of phacellae characteristic of *Carybdea.*

So far as can be judged, from published accounts, and by the specimens (Atlantic and Pacific) that I have myself examined, the members of the *alata-grandis* group, so far named, represent only one species, including *C. madrasputana* recently described by Menon (1930) which seems to represent an immature stage in development. It is even doubtful whether any of the named forms deserve the term variety.

Group C. Mayer (1900; 1910) described (as *C. aurifera*) a juvenile *Carybdea* from the Tortugas, differing from *C. xaymacana* in the facts that the velar canals next the tentacular radii were broadly palmate, and that the exumbrella was sprinkled with nematocyst warts, as well as in strong coloration. Recently, Stiasny (1926) has described a second species, *C. sivickisi,* from the Philippines, in which all the canals are of this palmate form, and with similarly warty exumbrella. Its rhopalar nitches also differ from those either of the *marsupialis* group, or of the *alata* group, in lacking a well-developed covering scale. But it is separated from *aurifera* by the fact that its exumbrella is strongly sculptured; that it has large gonads though only slightly larger (10-12 mm. high, as against 7 mm.); and in the tentacles and sensory nitches. Examination of a larger series alone can show how far these differences can be credited to different stages in growth; especially since Mayer's figures of *aurifera* are evidently somewhat diagrammatic and conflicting as regards the phacellae; meantime the two species are best retained.

Summation of the foregoing yields the following synopsis of *Carybdea,* as here recognized:

1. Tentacles simple.
    - A. Sensory nitches overhung by well developed covering scales; exumbrella not warty.
        - a. With prominent exumbral sculpture; sensory nitches with covering scale above, but entry open below.
            - (1). Phacellae dendritic, the filaments primarily arising from a single trunk.. *marsupialis* (including *xaymacana* and *murrayana*).
            - (2). Phacellae more diffuse, of several trunks arranged in a row ....*rastonii.*
        - b. Exumbrella without prominent sculpture; sensory nitches enclosed by a pair of scales below, as well as by one above..*alata.*
    - B. Sensory nitches without well developed covering scale, exumbrella warty ....*sivickisi* (*aurifera?*).
2. Tentacles bearing lateral branches..*stiasnyi.*

Carybdea marsupialis xaymacana Conant.

Charybdea xaymacana, Conant, 1897, p. 8, Fig. 8; 1898, p. 4, Figs. 1-16, 31-34, 36-43, 57, 67, 69, 70, 72; Berger, 1898, p. 223; 1900, p. 1, 3 pls.; Mayer, 1904, Pl. 7, Fig. 60; 1910, p. 509, Pl. 56, Figs. 5-7, Pl. 57, Fig. 1; Stiasny, 1919, p. 34.

Tamoya punctata, Fewkes, 1883, p. 84, Pl. 1, Figs. 4-6.

Material: Net No. 745, Surface, June 29, 1930, 4 specimens, about 12-23 mm. high.

Net No. 840, Surface, September 3, 1930, 1 specimen, about 11 mm. high.

Dip net, Surface, October 16, 1930, 1 specimen about 15 mm. high.

Net. No. 935, 1,463-0 meters, September 23, 1930, 1 specimen, about 19 mm. high.

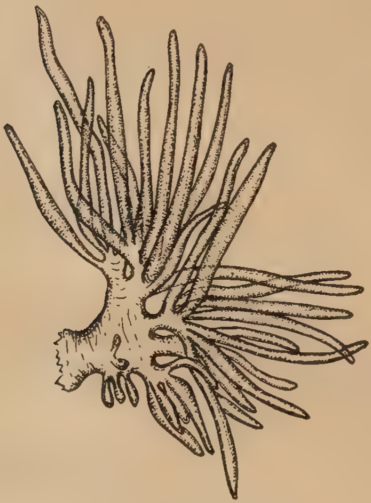
Net No. 977, Surface, May 12, 1931, 14 specimens, about 10-20 mm. high.

Net No. 978, Surface, May 15, 1931, 18 specimens, about 10-18 mm. high.

Net No. 979, Surface, May 16, 1931, 66 specimens, about 10-19 mm. high.

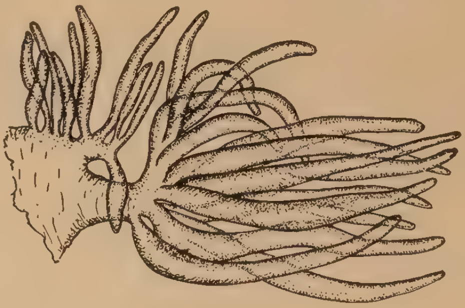
The general features of *xaymacana*, including exumbral sculpture, need no comment here, having been well described by Conant (1898) and by Mayer (1910); the phacellae, and rhopalar nitches in more detail by Stiasny (1919). But notes are pertinent on the range of variation in these respects, and on the branching of the velar canals, questions bearing on the relationship of this form to typical *marsupialis* on the one hand, and to *rastonii* on the other.

Phacellae: Conant (1898) and Stiasny (1919) both describe the gastric cirri of each group as arising from a single trunk, as is likewise the case



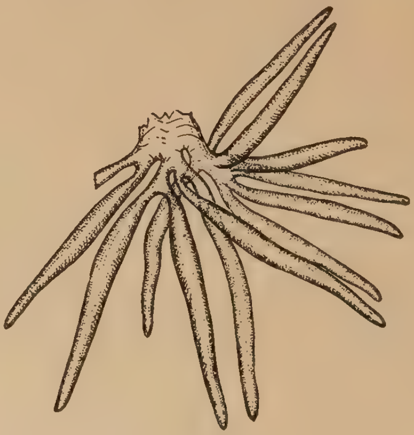
Text-fig. 3.

Carybdea marsupialis xaymacana. One of the groups of phacellae from a specimen 16 mm. high (Net No. 745), showing the typical state in which the filaments all arise from a single primary trunk. x 30.



Text-fig. 4.

Carybdea marsupialis xaymacana. One of the groups of phacellae from a specimen 23 mm. high (Net No. 745). x 30.



Text-fig. 5.

Carybdea marsupialis xaymacana. One of the primary branches, with terminal filaments, from the group of phacellae shown in Text-fig. 3.

in most of the Bermudian specimens (Text-fig. 3). And while in one of the clusters in the specimen from Net No. 745 (Text-fig. 4), there is a secondary cluster of filaments close beside the primary group (the other 3 phacellae are of the more usual type), the fact that the primary trunk invariably bears most, if not all of the cirri, is a ready distinction between *xaymacana* and juvenile *alata* of the same size (p. 147).

According to Stiasny (1919, p. 36), the filaments are not branched[17]; and they present this same appearance of simplicity when viewed through the bell wall. But when the groups are dissected out and the filaments teased apart (Text-figs. 3-5), it is seen that actually, the basal trunk gives rise to several primary branches, each of which in turn divides, close to the base, into a group of filaments, much as is the case in the typical *marsupialis* (p. 137). In one group, 5 such primary branches were detected, with a cluster of juvenile filaments at one side, apparently forecasting the development of a sixth; the total number of filaments being about 40 (Text-fig. 3).

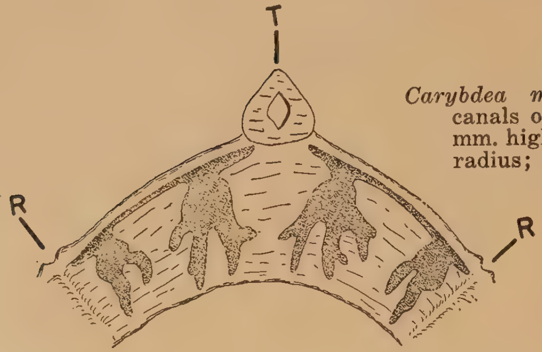
Canalization: Up to the present time, Stiasny (1919) alone has reported any variation (3) from the number of velar canals per quadrant (4) originally reported by Conant; even when most deeply forked, the 4 primary trunks are identifiable as such in all specimens I have seen. However, the present series amplifies earlier accounts, in showing considerable variation in the degree and type of branching. Conant's (1898, Figs. 3-5) original figures pictured all of the canals, in adult medusae, as forked, either bifid or trifid. Mayer's (1910, Pl. 56, Fig. 7) illustration, however, shows each of the four canals in one quadrant as four-branched. And the present series proves that there may be as many as 5 terminal subdivisions, with indications even of a sixth (Text-fig. 6). On the other hand, Stiasny (1919) found most of the canals in Haitian specimens of large size (22-25 mm. high) to be unbranched, except for a tendency to dichotomous division at the tips. And the Bahaman specimens listed above are of this same type, the canals being simple (Text-fig. 7), though the specimens—evidently full-grown, or nearly so, judging from the large gonads (p. 144.)—are otherwise indistinguishable from the Bermudian series, and from the specimens originally described by Conant (1898) from Jamaica. Since both the simple types of canalization and the more complex have been found in the West Indian region (and exclusively one or the other at any one locality on a given occasion), it is likely that we have here to do with a case of what has been termed "swarm" variation.

The Bermudian series, added to earlier accounts, shows that when the canals are branched, there is much variation in the degree and type of subdivision, even from canal to canal in a given individual, though in most (if not all) cases, it is primarily a dendritic forking, very different from the lateral lobation such as characterizes *Tamoya* (p. 154, Text-fig. 22). And only a very rough correlation—if any—exists between the complexity of branching and the size of the medusa. Thus, the canals may already be bifid and trifid, in specimens not more than 10-14 mm. high as exemplified by the specimen from Net No. 745. One of 19 mm., shows much the same state, but one of 23 mm. (Text-fig. 6) shows a somewhat more complex branching. In most cases, the canals next the tentacular radii are somewhat more complexly branched than those next the rhopalar radii (Text-fig. 6); occasionally, however, one of the latter may have as many as four well developed branches.

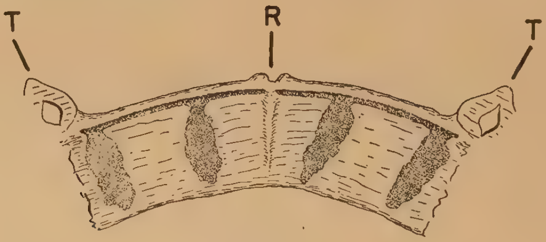
Pedalia: The only variations, worth mention, from the shape illustrated by Conant (1898) and by Mayer (1910) are slight individual differences in the precise outline of the fin-like basal expansion of the inner (oral) side

---

[17] Conant (1898, p. 14) was not explicit on this point.



Text-fig. 6.
Carybdea marsupialis xaymacana. Velar canals of one quadrant of specimen 22 mm. high (Net No. 745). **T.**, Tentacular radius; **R.**, Rhopalar radius. x about 6.



Text-fig. 7.
Carybdea marsupialis xaymacana. Velar canals of one quadrant of Bahaman specimen about 23 mm. high. x about 5.

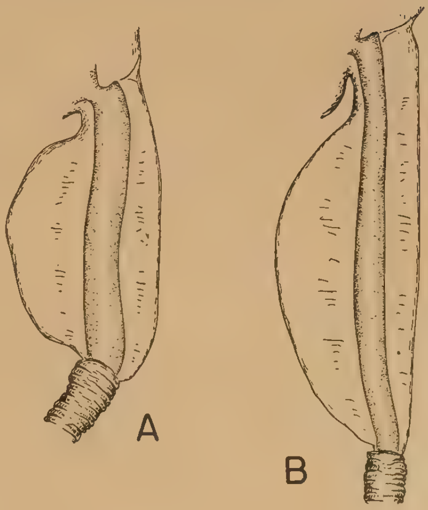
(Text-fig. 8). And these are so slight as to be perhaps explicable as contraction phenomena (Text-fig. 8). The pedalia of all I have seen agree very closely with these structures in an excellent specimen of typical *marsupialis* from Naples with which I have been able to compare them; also with *rastonii* (Bigelow, 1909, Pl. 10, Fig. 1; Uchida, 1929, Fig. 60A). The lengths of the pedalia, in terms of bell height, in a series of 10 specimens ranging in height from 10 mm. to 23 mm., are as follows:

Net No.	Bell Height.	Length of Pedalia.[18]	Pedalia, % of Bell Height.
977	10	6	60
745	12	5	42
977	15	7	47
977	16	8	50
977	17	8	47
977	17	8	47
977	17	8	47
745	19	8	42
935	20	9	45
745	23	10	43

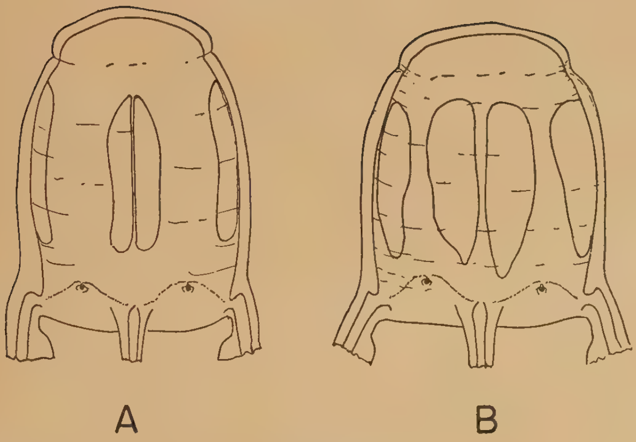
The foregoing shows some slight but irregular decrease in the relative length of the pedalia with the growth of the medusa; the average of 43% confirms Mayer's (1910) report of between ½ and ⅓ the bell heighth.

---

[18] Measured from the base of the fin-like expansion to the origin of the ringed portion of the tentacle.



Text-fig. 8.
Carybdea marsupialis xaymacana. Pedalia to show variations in outline. **A.**, From specimen 14 mm. high from Jamaica; **B.**, From Bahaman specimen 23 mm. high.



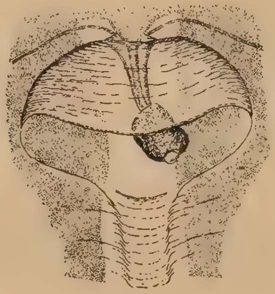
Text-fig. 9.
Carybdea marsupialis xaymacana. Outlines of two specimens about 20 mm. high to show variations in breadth and outlines of gonads. **A.**, From Net No. 979; **B.**, From Net No. 935.

Gonads: The feature which shows most obvious variation, among preserved specimens of a given size, is the relative length and breadth of the gonads. In their final state (Conant, 1898, Pl. 1, Fig. 1), these extend distally, nearly to the margin of the bell. None of the Bermudian or Bahaman specimens are, however, as far advanced as this. In the largest of the former, the gonads reach only to about the level of the distal ends of the rhopalia. In specimens 17-18 mm. high, i.e., ⅔ grown, the gonads terminate about as high above the rhopalia as are the latter above the bell margin. Among the Bermudian series, the gonads in specimens 18-23 mm. high vary from narrow-linear, to so wide that their free margins are close together (Text-fig. 9). Furthermore, the lamellae from which the sex organs arise, may be either so narrow that the gonads of each pair seem almost in union (Text-fig. 9A), or so wide that they are separated by a considerable space

(Text-fig. 9B). This last may mirror, simply, a flaccid condition. But the variation in length of the gonads, in specimens of equal size, is evidence that the growth of these organs does not necessarily parallel the growth rate of the medusa as a whole.

So far as can be determined in surface view, the Bermudian specimens are all males. Both sexes are, however, represented among the Bahaman series, the females being recognizable by the large eggs with which the leaf-like gonads are crowded, and which are easily visible with a hand lens.

Rhopalar Nitches: The present series confirms Stiasny's (1919) observation that the outlines of the pits in which the rhopalia are situated, and of the scales that partially cover the pits, offer specific characters in this genus. As Conant (1898, Pl. 1, Fig. 1) long ago showed (and Stiasny, 1919, Fig. 2 more recently), the covering scale of *xaymacana* (Text-fig. 10) has a simple undulatory outline, and the nitch is wide open toward the bell margin, i.e., there are no subsidiary scales such as characterize *C. alata* (p. 146). This is also true of typical *marsupialis*, as pictured by Claus (1878, Pl. 1, Figs. 1, 2), and as I have been able to verify on the specimen mentioned above; also in *C. rastonii* (Bigelow, 1909, Pl. 10, Fig. 1, 4; Uchida, 1929, Fig. 61).



Text-fig. 10.
Carybdea marsupialis xaymacana. Sensory pit, with covering scale, of a Bahaman specimen. x about 10.

General Distribution: Previous records of *xaymacana*, under this name, are all from the West Indian region; Jamaica (Conant, 1898); Bahamas (Mayer, 1904; 1910); Haiti (Stiasny, 1919). But it is no surprise to find it near Bermuda, for it is probable that the *T. punctata* recorded thence by Fewkes (1883) was actually a young *xaymacana*.

Vertical Range: The list of captures (see above) confirms previous experience that the species occurs chiefly close to the surface.

Carybdea alata Reynaud.

Carybdea alata, Reynaud, 1830, p. 95, Pl. 33, Fig. 1; Haeckel, 1880, p. 441; Vanhöffen, 1908, p. 34; Mayer, 1910, p. 510; Bigelow, 1918, p. 400.

Marsupialis alata, Lesson, 1843, p. 276.

Tamoya alata, L. Agassiz, 1862, p. 174; Rao, 1931, p. 27 [partim].
——, Semper, 1863, p. 561, Pl. 39, Figs. 8, 9.

Charybdea pyramis, Haeckel, 1879, Pl. 25, Fig. 5-8; 1880, p. 440.

Charybdella alata, Haeckel, 1880, p. 441.

Charybdea grandis, Agassiz and Mayer, 1902, p. 153, Pl. 6, Figs. 26-31; Bigelow, 1909, p. 19; Thiel, 1928, p. 4.

Charybdea moseri, Mayer, 1906, p. 1135, Pl. 1, Figs. 2-26.

Carybdea alata var. *pyramis,* Mayer, 1910, p. 511.

Carybdea alata var. *grandis,* Mayer, 1910, p. 511; 1915, p. 171; 1917, p. 189; Light, 1921, p. 26.

Carybdea alata var. *moseri,* Mayer, 1910, p. 512; Light, 1914, p. 196; Stiasny, 1919, p. 37.

Charybdea madraspatana, Menon, 1930, p. 3, Pl. 1, Fig. 3.

? ——, Semper, 1863, p. 561, Pl. 39, Fig. 8.

? *Charybdella philippina,* Haeckel, 1877, No. 404.

? *Charybdea philippina,* Haeckel, 1880, p. 440.

? *Charybusa obeliscus,* Haeckel, 1877, No. 406.

? *Charybdea obeliscus,* Haeckel, 1880, p. 441.

? *Charybdea* sp? Browne, 1905, p. 157.

Non *Tamoya alata,* Uchida, 1929, p. 172; Stiasny, 1929, p. 196; 1930, p. 5; 1935, p. 10; 1937, p. 210.

Material: Net No. 448, 732-0 meters, September 9, 1929, 1 specimen, about 75 mm. high.

Net No. 459, 732-0 meters, September 11, 1929, 1 specimen, about 20 mm. high.

Net No. 663, 732-0 meters, June 4, 1930, 1 specimen, about 80 mm. high.

Net No. 979, Surface, May 16, 1931, 1 specimen, about 90 mm. high.

Also, 4 specimens, 55-63 mm. high, from Jamaica, in the collection of the Museum of Comparative Zoology.

For the reasons for the choice of *alata* Reynaud (1830) as the name for this species, see p. 138. Apparently, the next record of it was one of Semper's (1863, Pl. 39, Fig. 9) unnamed carybdeids from the Pacific; while a second of his unnamed forms (Semper, 1863, Pl. 39, Fig. 8), may have been a young stage of it, judging from the number (6) of canals in one quadrant.[19] It is for this same reason that *C. obeliscus* Haeckel is provisionally included here in the synonymy of *alata.* As Mayer (1910) has already decided, this seems certainly to apply to Haeckel's *C. pyramis,* for the latter had not only the number of canals now known to be characteristic of *alata,* but also the lunate groups of phacellae, while the relatively great length of its pedalia is explicable as associated with the small size of Haeckel's specimen (20 mm. high).

So far as I am aware, *alata* was not seen again until 1902, when Agassiz and Mayer gave the first adequate description of it (large adult), from the tropical Pacific, as *C. grandis,* followed by Mayer's (1906) account of half-grown (or dwarf) examples, from the Hawaiian Islands, as *C. moseri.* Browne (1905) had meantime reported, from Ceylon, a small *Carybdea* that may have been of this parentage, though its velar canals were less numerous. Soon thereafter it was reported from the South Seas (Bigelow, 1909, p. 20) and from Philippine waters (Mayer, 1915; 1917, "*C. alata* var. *grandis*").

Since that time, specimens definitely referable to *alata* have been reported from Sumatra (Stiasny, 1919) and from the west tropical Pacific (Mariana Islands; Thiel, 1928) in the one hemisphere, from the Florida-Bahamas region (Bigelow, 1918) and from unnamed Atlantic localities (Thiel, 1928) in the other. The figures by Menon (1930) of his *C. madraspatana* from India, also agree closely with *C. alata,* so far as general form and shape of pedalia are concerned, while the depression of the apex, thought by him to be distinctive, seems more likely to have been the result of contraction, or of distortion. And as the large number (up to 10) of canals per quadrant, reported (but not figured) by Menon may likely be derivable from the primary 6, characteristic of *alata*, it seems probable that *madraspatana* belongs in the synonymy of the latter. Some of the specimens recorded by Rao (1931) as *Tamoya alata* seem also to belong here, because of the number (6 per quadrant) and simplicity of their canals, whereas others (because of complexity of the latter) seem to have been true *Tamoya*.

---

[19] This later formed the basis for Haeckel's (1880) *Charybdea philippina.*

As no account—other than Reynaud's (1830) original—of the Atlantic representatives of this species has ever appeared, details are added here, as warrant for definitely uniting it with its Indo-Pacific relative. The latter has been redescribed by Stiasny (1919).

General Form: The Atlantic series agrees with previous accounts in being not only of large size, and in the absence of any pronounced exumbral sculpture, but in the fact that the bell is relatively narrower than in any member of the *marsupialis* group; measurements are as follows:

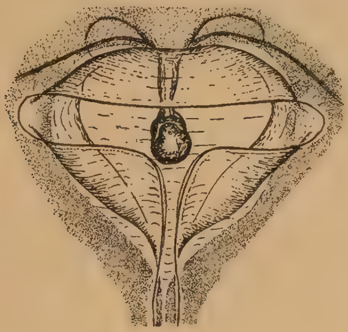
Net No.	Approximate Height in mm.	Approximate Breadth in mm.	Pedalia, % of Bell Heighth.
459	20	14	70
663	80	43	56
979	85-90	42	50 (approx.)
Also, Jamaica	63	35	55
"	60	35	60
"	60	35	60
"	55	35	64
			62%, average

In the Indo-Pacific examples, measured by Agassiz and Mayer (1902), by Mayer (1906; 1915; 1917), and by Stiasny (1919), the width also averaged 50-60% of the height, contrasting with an average of about 80% in *xaymacana*, and in the *marsupialis* group generally. However, there is no specific discontinuity in this respect—not, at least, in preserved specimens—for Mayer (1915; 1917) has reported large *alata* (as var. *grandis*) from the Philippines, in which the heighth was 73% and 81% of the breadth. It should be noted, however, that preserved specimens are usually so much flattened that breadth is exaggerated. And the better preserved of the *alata* I have seen all taper toward the apex, which is not normally the case in *marsupialis* and its immediate allies.

In the specimens of *alata* I have seen, exumbral sculpture has been confined to a faint trace of a circumferential furrow, at the level of the base of the stomach, and to the prominences in which the rhopalar nitches are situated; nor has any trace of the longitudinal ridges and furrows, so prominent in the *marsupialis* group, been reported by any observer for *alata;* neither have nettle warts.

Rhopalia: In the largest two of the Bermudian specimens, the distance of the rhopalia above the bell margin equals about 12% of the bell heighth; about 15% in the somewhat smaller Jamaican examples, about 15-20% in the smallest Bermudian, while in Indo-Pacific specimens, so far measured, it has ranged from 13-19% (Agassiz and Mayer, 1902; Mayer, 1906; 1915; 1917; Stiasny, 1919).

Rhopalar Nitches: The series confirms Stiasny's observation that these differ from the nitches of the *marsupialis* group, in being partially covered, on the side toward the bell margin, by scale-like projections of the umbrella on either hand, in addition to the roof-like scale that overhangs the nitch from above; a difference illustrated by Text-fig. 10, compared with Text-fig. 11 (cf. also Text-fig. 20 of *Tamoya haplonema*).



Text-fig. 11.
Carybdea alata. Sensory pit, with covering scales, of specimen from Net No. 979. x about 6.

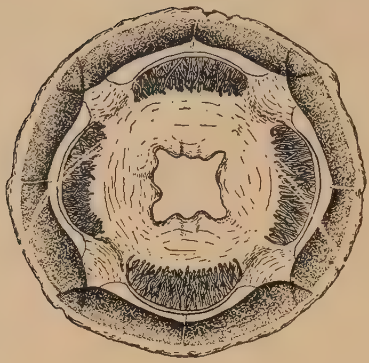
Gonads: No gonads are visible on the 20 mm. specimen, but as this is in poor condition, they may have been lost. In the 80 mm. specimen, they reach about to the level of the rhopalia; to a point about halfway between the latter and the bell margin in the 90 mm. specimen. Perhaps as the result of contraction of the bell, they overlap somewhat near their upper ends in the 80 mm. specimen (Text-fig. 12).

Stomach: As the name *alata* has also (but incorrectly) been applied to a *Tamoya* from the Indo-Pacific, it should be emphasized, as Stiasny (1919, p. 37) has pointed out, that in *Carybdea alata,* the stomach is flat and with very short lips, much as it is in *C. marsupialis,* and with no trace of mesenteries; indeed it is so shown in Agassiz and Mayer's (1902) and Mayer's (1906; 1910; 1915) illustrations.

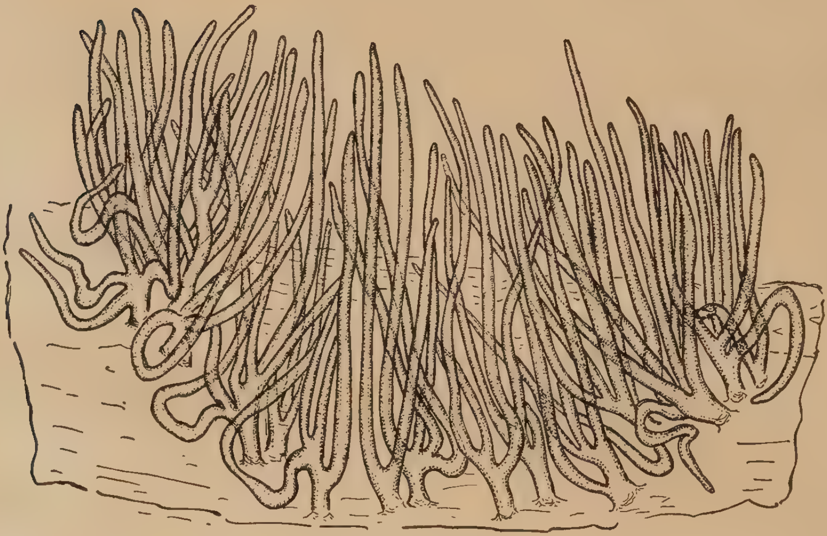
Phacellae: Previous students have already shown that the numerous gastric cirri of each group, occupy crescentic areas extending horizontally, at the corners of the stomach (Text-fig. 12), an arrangement differing sharply from the dendritic phacellae of the *marsupialis* group (p. 140); but no detailed account of these structures in *alata* has yet appeared. In the best preserved of the Bermudian series, the 4 crescents occupy about ⅔ of the periphery of the stomach (Text-fig. 12) confirming Agassiz and Mayer's and Mayer's illustrations. Stiasny (1919, p. 37) has described the filaments as "einfach, unverzweigt." And in surface view, the Bermudian specimens presented this same appearance. But when one cluster (Text-fig. 13) was dissected, and its component filaments spread apart it proved that the latter are the terminal branches of numerous primary trunks, standing in a single row. In most cases, a primary trunk bears 2-8 such branches (Text-fig. 14). It is the fact that the end filaments are much longer than the (very short) primary trunks that gives the deceptive appearance of simplicity. In one group of phacellae examined, there were approximately 20 primary trunks, and more than 75 filaments. As Uchida (1929) has expressed doubt, whether Atlantic specimens earlier recorded by me (Bigelow, 1918, p. 400) as *alata* really belonged to this species, I may note that one of these in the collection of the Museum of Comparative Zoology, has phacellae of this same type, besides agreeing with the Bermudian series in other respects.

The fact that the small specimen, 20 mm. high, has only 6-8 primary trunks, in each crescentic cluster, contrasted with the much larger number in large specimens, gives a measure of the increase in number that takes place with growth.

Canals: All recent accounts credit this species with 6 velar canals per quadrant, as is also true of the Bermudian specimens (Text-fig. 15); evi-

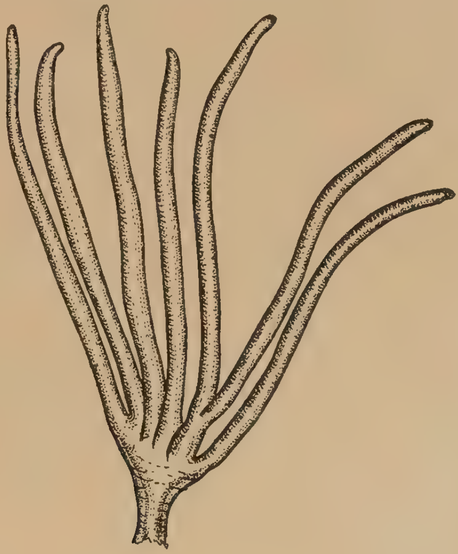


Text-fig. 12.
Carybdea alata. Somewhat schematic apical view of specimen 75 mm. high, from Net No. 448, to show the location of the lunate groups of gastric filaments.



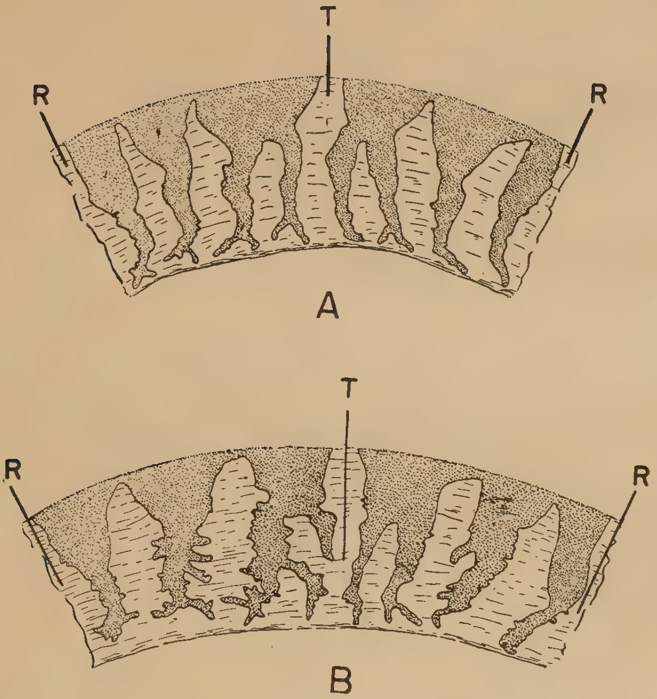
Text-fig. 13.
Carybdea alata. One cluster of gastric filaments, specimen from Net No. 448. x about 12.

dently, variants from this state are rare, except that a canal next one of the tentacular radii may be so deeply cleft that unless it be traced back to its proximal end, it might appear that the primary number was greater (Text-fig. 15B). Evidence thus accumulates to the effect that the number of canals is a dependable specific difference between *alata* and the *marsupialis* group (p. 141). Accounts have, however, differed widely as to the extent to which the canals branch. On the other hand, Mayer (1906) and Stiasny (1919) have described them as simple, or at most as showing the commencement of division. But Agassiz and Mayer (1902), copied by Mayer (1910), picture them as digitate, with short lateral lobes, while in Vanhöffen's (1908) two specimens, they were variously forked—those of the tentacular radii usually the most deeply. And the two large Bermudian specimens not only show forking, with similar contrasts between the perradial and the interradial pairs, and with complexity increasing with growth (cf. Text-fig. 15A with Text-fig. 15B), but also with wide variation from octant to octant even of



Text-fig. 14.

Carybdea alata. One primary branch with terminal filaments, from the group of phacellae in Text-fig. 13.



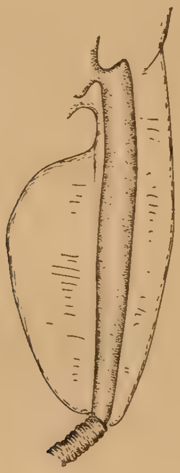
Text-fig. 15.

Carybdea alata. To show velar canals. **A.**, One quadrant of velarium of specimen about 75 mm. high from Net No. 448; **B.**, One quadrant of specimen about 90 mm. high, from Net No. 979. **T.**, Tentacular radii; **R.**, Rhopalar radii. x about 3.

a given specimen, in the precise degree of subdivision, and in the lateral lobing of the canal margins.

Pedalia: By earlier accounts, and in the Bermudian and Jamaican series, the length of the pedalia (measured along the inner edge) equals about 25-30% of the bell heighth, in medium-sized specimens of 60-90 mm. In larger specimens they are relatively shorter: 17% according to Agassiz and Mayer (1902) at a bell heighth of 230 mm. In young specimens they are relatively longer: 33% in the Bermudian example of 20 mm.; and shown as about 50% in a young medusa by Agassiz and Mayer (1902).

The fin-like expansions of the pedalia are relatively narrower in the Bermudian and Jamaican specimens (Text-fig. 16) than they are pictured by Agassiz and Mayer (1902, Pl. 6, Fig. 37) or by Mayer (1906, Pl. 1, Fig. 2; 1917, Fig. 3); their outlines less pronouncedly semi-lunar. But this may well be the result of different states of contraction, between preserved and fresh material.



Text-fig. 16.
Carybdea alata. Basal part of tentacle of specimen from Net No. 448.

General Distribution: The wide distribution, Atlantic and Pacific, of locality records for this species (listed above), suggests that it is cosmopolitan, in the warm belts of the oceans. But it probably does not occur in the Mediterranean (perhaps barred thence by low water temperatures), for it could hardly have been overlooked there.

Tamoya.

If the *Bursarius cytherae* of Lesson (1830, p. 108, Pl. 14, Fig. 1) was, in fact, congeneric with the form later named *Tamoya* by F. Müller (1858), as Haeckel (1880) suggested, it would be necessary to substitute *Bursarius* as the generic name. However, as Haeckel pointed out, Lesson's account and illustration differ from all known carybdeids in showing only 2 tentacles (though 4 pedalia); nor do they give any indication as to the structural characters which determine generic position in this group. It is thus wisest to abandon the name *Bursarius* for good and all, on the ground that the type species of the genus is and must always remain unrecognizable. For this same reason the specific name *bursaria*, substituted by Haeckel (1880) for Lesson's *B. cytherae*, is likewise best regarded as a *nomen nudem*.

During the years that have elapsed since the type species of the genus *Tamoya* (*T. haplonema*) was described by Müller (1858), carybdeids that can be referred to this genus as here defined[20] have been described from the two sides of the Atlantic (Haeckel, 1880, as *"T. prismatica"*; Mayer, 1910; Stiasny, 1934); from Samoa (Haeckel, 1880); from Japan (Uchida, 1929); from the Malay Archipelago (Stiasny, 1919; 1930); and from India (Menon, 1930; Rao, 1931); showing a world wide distribution within the warm belt.

All Atlantic records undoubtedly belong to *T. haplonema.* And so far as can be judged from available information, all Indo-Pacific Tamoyas so far reported also represent a single species. But it is still an open question whether or not the Atlantic and Indo-Pacific forms are distinct. If so, the correct name for the Indo-Pacific species is *gargantua,* for the earliest named Indo-Pacific carybdeid that is definitely proved, by the description, to have been a *Tamoya,* is the *T. gargantua* of Haeckel (1880), for which he revived a name under which Lesson (1830) had long before reported a large carybdeid from New Guinea. And while neither Lesson's account, nor his illustration, gave any indication of the details needed to show whether his specimen was actually a *Tamoya,* or a large *Carybdea,* stability of nomenclature will be served by following Haeckel in this regard. Should the Atlantic and Pacific Tamoyas be finally united, *haplonema* would become a synonym of *gargantua.*

Reasons are given above for abandoning altogether the specific name *bursaria* which Haeckel (1880) substituted for Lesson's *Bursarius cytherae,* on the assumption that it also was a *Tamoya.*

Tamoya haplonema Müller.

Tamoya haplonema, Müller, 1858, p. 1, Pl. 1, 2; L. Agassiz, 1862, p. 174; Haeckel, 1880, p. 443; Brooks, 1882, p. 138; Von Lendenfeld, 1884, p. 245; Mayer, 1904, p. 28, Pl. 7, Figs. 60-64; 1910, p. 513, Pl. 57, Fig. 2; Stiasny, 1934, p. 339.

Tamoya prismatica, Haeckel, 1880, p. 443.

Charybdea (*Tamoya*) *haplonema,* Fewkes, 1889, p. 526.

Non *Tamoya haplonema,* Boone, 1933, p. 39, Pl. 6.

Material: Surface, June 25, 1929, 1 specimen, heighth about 70 mm., breadth about 45-50 mm. (depending on the degree of flattening), length of pedalia along inner edge, about 22 mm., of fin-like expansion of latter, 15 mm., heighth of rhopalia above bell margin, 13 mm.

Although the Atlantic species of *Tamoya* has been mentioned repeatedly, by name, in the literature of medusae, few students have been fortunate enough to have seen specimens of it. First described by Müller (1858), it was next reported by Haeckel (1880) whose description (as *"T. prismatica"*) of a West Indian specimen agreed so closely with the original account, both in arrangement of phacellae, in size of stomach, and in complexity of velar canals, as to make it certain that he was dealing with *haplonema.* As the next reports were by name only (Brooks, 1882; Fewkes, 1889), it is possible that they may actually have referred to some *Carybdea.* And the *"T. haplonema"* recorded from the Bahamas by Boone (1933, p. 39, Pl. 6) seem certainly to have been *Carybdea* (probably *C. xaymacana*), for her illustration shows a very flat stomach, with brush-like groups of phacellae at its corners.

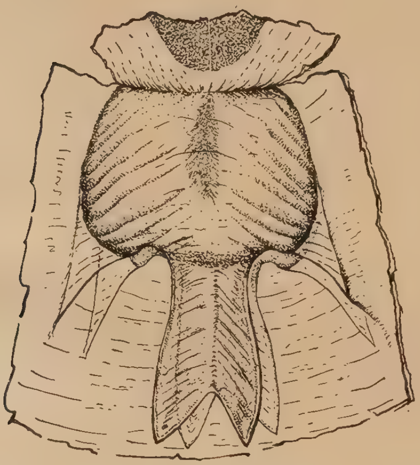
Mayer (1904; 1910), however, had typical examples of *T. haplonema,* as had Stiasny (1934) more recently.

The single Bermudian specimen (considerably crumpled) agrees so closely in general form with Mayer's (1910, Pl. 57, Fig. 2) picture that illustration is not required.

---

[20] Omitting references by name only.

In the preserved condition, the gelatinous substance is stiffer than in any other carybdeid I have seen. And the nematocyst warts described by previous students (see particularly, Stiasny, 1934) are still to be seen thickly strewn here and there on the exumbrella down to the bell margin, likewise on the outer faces of the pedalia, though the surface has been so badly rubbed that nothing can be said as to the regularity of their distribution. As the size of the stomach is a distinctive feature of the genus, I may note that this organ (Text-fig. 17) is about as long as shown by Müller (1858, Pl. 1, Fig. 1) and by Mayer (1910, Pl. 57, Fig. 2), i.e., with lips hanging to about the mid-level of the bell; this is somewhat shorter than in Stiasny's (1934) West African specimen—a difference perhaps due to the degree of contraction. The well differentiated, pointed lips are also much as pictured by Müller and by Stiasny. They are not shown clearly by Mayer (1910, Pl. 57, Fig. 2).



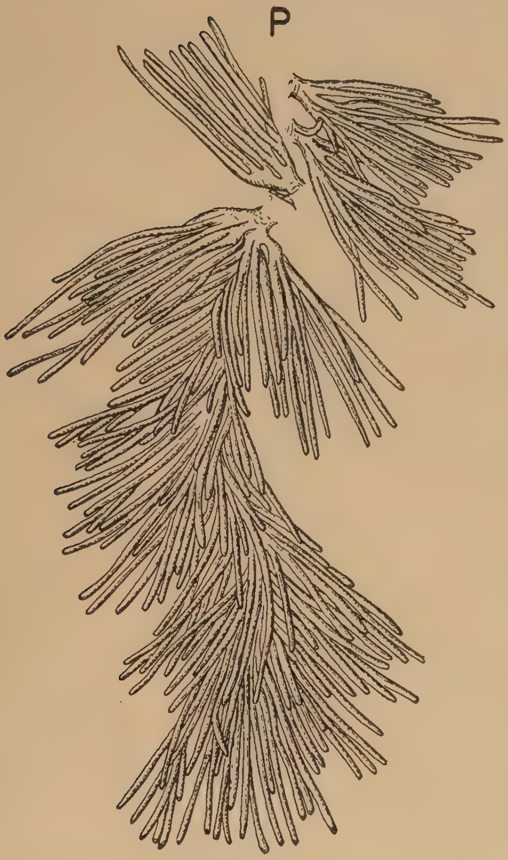
Text-fig. 17.

Tamoya haplonema. Dissection of upper part of bell of Bermudian specimen, to show outlines of stomach, lips, mesenteries, and area occupied by the phacellae. Somewhat schematic.

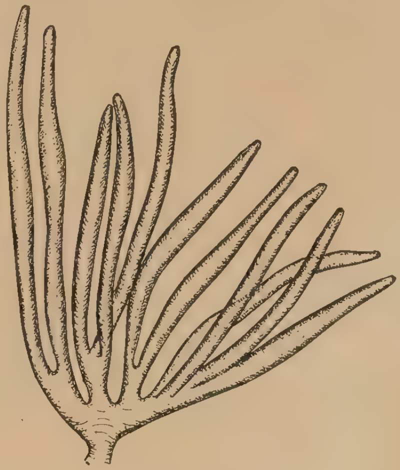
Mesenteries: Previous statements regarding mesenteries in *Tamoya* have been conflicting. According to Müller (1858) and to Haeckel (1880), the pendulous stomach is bound to the subumbrella by well developed mesenteries in the radii of the rhopalia, as Uchida (1929) also found for the Pacific *Tamoya.* Stiasny (1919, Fig. 6; 1934, Fig. 1), however, pictures the mesenteries as in the radii of the tentacles; while Mayer (1910, p. 512) states that the "so-called mesenteries . . . are merely the flattened perradial sides of the cruciform stomach."

It is therefore worth mention that the Bermudian specimen confirms early accounts, in the presence of mesenteries (Text-fig. 17), and that the latter are in the radii of the rhopalia (perradial). Structurally, they are thin, transparent plates (apparently ectodermic), their free margin crescentic, and by connecting the 4 sides of the stomach with the exumbrella, they subdivide the upper part of the bell cavity into as many blind pockets.

Phacellae: The gastric cirri agree with previous accounts, in being grouped in 4 bands extending vertically along the sides of the stomach, alternating with the lips, i.e., in the radii of the tentacles (thus interradial, as is also the case in *Carybdea*). In Stiasny's (1934) illustration, these bands are shown extending as far as the distal end of of the dilated portion of the manubrium. In the present example, however, they reach only about



Text-fig. 18.
Tamoya haplonema. One of the groups of gastric filaments of the Bermudian specimen. **P.**, Proximal end. x about 10.

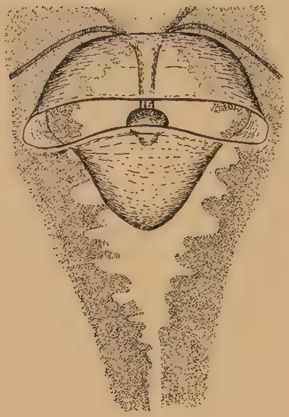


Text-fig. 19.
Tamoya haplonema. One of the primary trunks with terminal filaments, from the group illustrated in Text-fig. 18. x about 18.

to the mid-level of the latter (Text-fig. 17). As no detailed account has previously appeared, I should add that each group consists of a single row of about 40 primary trunks, arranged (but somewhat irregularly) in a single row, and each dividing, close to its base into several filaments (Text-figs. 18, 19).

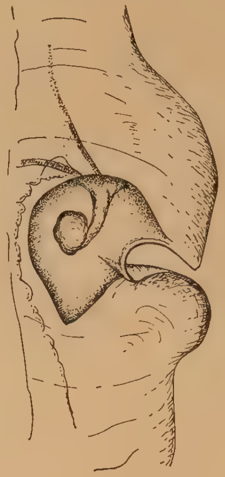
Rhopalar Nitches: Earlier accounts (Müller, 1858, Pl. 1, Fig. 1; Stiasny, 1919, p. 39, Fig. 7; 1934, p. 341, Fig. 1B; Uchida, 1929, Fig. 81B) had already shown that the shape of the rhopalar nitches is one of the minor characters separating *Tamoya* from *Carybdea.* In *T. haplonema* (and in its Pacific relative also), the nitches, situated on well marked, ovoid gelatinous prominences of the exumbrella (Text-figs, 20, 21), are continuously bounded, on the lower side as well as on the upper, by a rounded covering-scale, which gives the nitch a pit-like confirmation, very different in appearance, from the more open nitches of *Carybdea* (cf. Text-fig. 20, with Text-figs. 10, 11).

The edges of the marginal pouches, where they enclose the nitches, and for some distance beyond, are strongly lobate (Text-fig. 20); in *Carybdea* (Text-fig. 10), they are smooth.



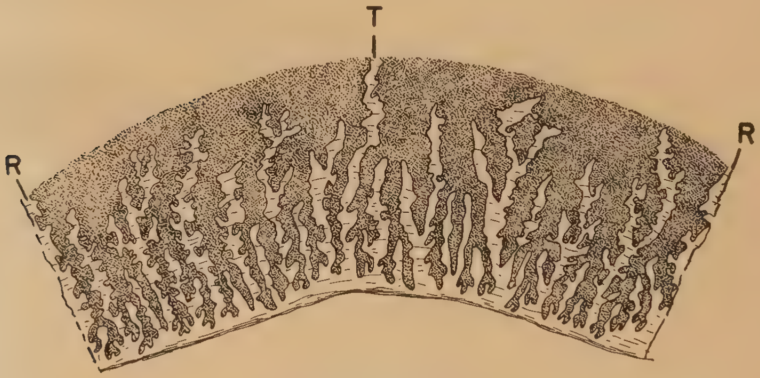
Text-fig. 20.

Tamoya haplonema. One of the sensory nitches of the Bermudian specimen, to show covering scales and lobate outlines of the marginal pouches. x about 7.



Text-fig. 21.

Tamoya haplonema. Lateral view of sensory nitch. x about 6.



Text-fig. 22.

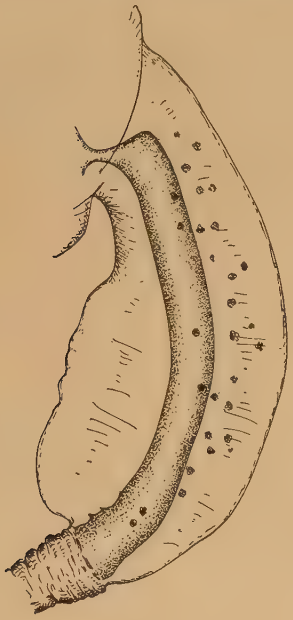
Tamoya haplonema. One quadrant of velarium of Bermudian specimen to show velar canals. **T.**, Tentacular radius; **R.**, Rhopalar radius.

Canals: The readiest field-mark to distinguish *Tamoya* from any *Carybdea* yet described is the lobing of the margins of its complexly forked velar canals (Text-fig. 22); this type of branching was long ago pictured by Müller (1858); more recently by Stiasny (1919, Figs. 8, 9; 1934, Fig. 1, C), and by Uchida (1929, Fig. 85).[21] Previous authors (Mayer, 1910; Stiasny, 1934) record 10 canals per quadrant for *T. haplonema.* In the Bermudian specimen, the number is less regular, there being only 3 primary canals in one octant (between tentacular and rhopalial radii); but so complexly subdivided that there are 33 terminal branches, whereas in the adjacent quadrant, the number of major trunks is 7 (some of which may have been derived by subdivision close to the base) with 30 terminal branches.

---

[21] Mayer's (1910, Pl. 57, Fig. 2) picture suggests a somewhat different type of subdivision, but it is evidently diagrammatic.

Pedalia: These (Text-fig. 23) are intermediate in outline between those figured by Mayer (1910, Pl. 57, Fig. 2) and by Stiasny (1934, Fig. 1a). According to Mayer's figure, the tentacular canals are widely dilated at the distal ends of the pedalia, whereas Stiasny shows them as of uniform bore. Here, again, the present specimen is intermediate, the canals showing only slight dilation distally, but with an irregularity of the margins suggesting that when the pedalia are relaxed, the dilation might be greater.



Text-fig. 23.
Tamoya haplonema. Basal part of tentacle. x about 2.

Gonads: These organs are somewhat farther advanced in development than those pictured by Mayer, not only reaching about to the level of the points of origin of the tentacular canals, but so broad that their free edges overlap slightly. In their present state, they are folded, but so irregularly as to suggest the effects of preservation.

General Distribution: Previous records of *T. haplonema* include Brazil (the type locality); West Indies; east coast of the United States, north to Latitude about 41° N., and to the offing of the French Congo.

Periphylla.

Periphylla hyacinthina Steenstrup.

For early synonymy, see Mayer, 1910, p. 544, 546 ("*P. hyacinthina*" and "*P. hyacinthina* forma *regina*").

For subsequent discussions, see especially Broch, 1913, p. 4; Stiasny, 1934, p. 342.

Material: Net Nos. 13, 16, 17, 23, 26, 33, 34, 39, 43, 44, 45, 53, 83, 88, 89, 100, 103, 114, 116, 119, 121, 135, 141, 142, 144, 145, 154, 157, 178, 196, 221, 234, 235, 240, 241, 261, 267, 269, 270, 273, 274, 278, 279, 280, 291, 292, 293, 295, 296, 405, 434, 449, 543, 545, 546, 547, 548, 551, 552, 555, 562, 577, 581, 590, 595, 618, 619, 620, 621, 624, 625, 626, 631, 638, 644, 645, 646, 654, 674, 686, 688, 692, 699, 707, 709, 710, 712, 716, 721, 722, 723, 724, 726, 728, 730, 731, 732, 734, 736, 746, 750, 752, 756, 758, 759, 762, 766, 767, 772, 773, 774, 775, 778, 780, 785, 791, 795, 796, 797, 798, 799, 801, 804, 809, 818, 822, 825, 827, 832, 835, 836, 837, 838, 842, 846, 848, 850, 851, 852, 854, 855, 858, 860, 880, 882, 883, 885, 886, 895, 896, 898, 905, 916, 917, 918, 921, 925, 928, 930, 932, 933, 935, 937, 939, 940, 951, 963, 970; 317 specimens; 1-14 (in most cases, 1-3) per haul.

Successive studies (see especially Stiasny, 1934) have now definitely established that the two representatives of this genus most often reported —*dodecabostrycha* and *hyacinthina*—are nothing more than growth stages, contraction phases, or color variants of one species; and that this probably is equally true of the third, *regina*. Stiasny (1934, 1937), on the basis of the *Discovery* collection, has concluded that the three represent successive stages in growth, the *dodecabostrycha* form (small, with low rounded stomach and transparent peripheral zone) being the youngest, the *hyacinthina* form (with peripheral entodermal system also pigmented, and usually with high, pointed stomach), an intermediate stage—usually 75-80 mm. in diameter—while the *regina* form represents the largest, usually more than 80 mm. in diameter, with extensive and dense peripheral pigmentation, but again usually low-domed, as are the juveniles.

The Bermudian series (many of which are in excellent condition) corroborates this general growth relationship, so far as the *dodecabostrycha* and *hyacinthina* types of pigmentation are concerned, for among 38 small specimens taken at random, 5-12 mm. in diameter at the level of the coronal furrow, 37 have the peripheral zone so hyaline that the gonads are entirely visible, only one being so densely pigmented that they are concealed. Among 37 specimens of 15-20 mm. the gonads are completely visible in only 21; their upper portions are obscured by the spreading pigment in 7; and completely so obscured (*hyacinthina* form) in 9. And among 27 specimens of 25-40 mm., the gonads are entirely obscured in 18; partially so in 8; and completely visible only in 1. However, still larger specimens occasionally retain the restricted ("*dodecabostrycha*") type of pigmentation; this being true of one Bermudian example of 45 mm.; and of another of 55 mm. The series does not include any specimens larger than 60 mm., hence, throws no additional light on the *regina* form.

It seems that the very smallest specimens (smaller, say, than 8-9 mm. in diameter at the coronal furrow) usually, or always, have the gastric floor low-domed. It is already more or less definitely conical, however, in the majority of the Bermudian specimens of 10-12 mm., in several cases pronouncedly so (extreme *hyacinthina* type). It has already been sufficiently emphasized, by various students, that medium-sized specimens show wide variation in this respect, with complete integradation from the lowest and rounded, to the highest and most acutely conical—depending, I believe, entirely on phases of contraction.

Broch (1913, p. 7) and Stiasny (1934, p. 356) have both observed that the apical projection of the aboral gastric wall into the mesoglea, so often observed in *Periphylla* and frequently referred to as a "stiel canal," does not occur in very small specimens. This the Bermudian series corroborates, for while the gastric apex is acutely conical in some, even of the smaller (down to 11 mm. in diameter at the level of the coronal furrow), the smallest in which the apex shows anything that could be named a canalar elongation is about 17 mm. in diameter. We can, then, finally conclude that this structure has nothing whatever to do with a true stiel canal—i.e., does not indicate derivation from a Scyphistoma stage, but merely represents one extreme in the phases of contraction that govern the contour of the floor of the stomach in middle-sized individuals.

It is interesting that, in *Periphylla* (as in *Atolla*, p. 161), the gonads appear while the medusa is still not more than 5-8 mm. in diameter at the level of the coronal furrow[22]. By the time a diameter of 15-20 mm. is reached, the sexual organs may be proportionately about as large as they are in large specimens, the females with large eggs. But we have still to learn through how extensive a growth-phase any individual specimen may actually set free its sexual produce.

General Distribution: Enough records have now accumulated to prove that *Periphylla* is truly cosmopolitan in seas of appropriate depth and temperature[23], Atlantic, Pacific, and Indian, right up to the polar fronts. Having been already taken in the Straits of Florida (Bigelow, 1918), and to the southeast of Bermuda (Bigelow, 1928), it was a foregone conclusion that any campaign of deep towing would yield it in the immediate vicinity of the latter.

Seasonal and Annual Distribution: The following tabulation of the percentage of the hauls, at 732-0 meters or deeper, that took *Periphylla* (the number taken shoaler was negligible) illustrates the relative frequency of occurrence, in different months, and as between the two years 1929 and 1930:

1929				1930			
Months.	Total Hauls.	Hauls with *P.*	% with *P.*	Months.	Total Hauls	Hauls. with *P.*	% with *P.*
April	47	13	29	April	......	......	......
May	75	15	20	May	87	26	30
June	93	9	9	June	82	23	28
July	107	14	13	July	52	23	44
Aug.	51	0	0	Aug.	11	1	9
Sept.	106	3	3	Sept.	136	43	31

Thus it appears that *Periphylla*—like *Atolla* (p. 163)—occurred with much greater frequency in 1930 than in 1929. But the annual difference in actual abundance was not as great for *Periphylla* (180 specimens in 343 deep hauls, or 0.5 per haul in 1930; 127 specimens in 462 deep hauls, or 0.3 per haul in 1929) as for *Atolla* (p. 162). And the data for the two years agree in showing the greatest frequency in spring and early summer, with a decided decrease in late summer, followed by some recovery in early autumn, especially in 1930.

The 95 hauls that yielded juveniles of 15 mm. or smaller, were well distributed through the season, most numerous and in roughly comparable numbers (17-23) for May, July and September, evidence that *Periphylla*, near Bermuda, reproduces throughout the spring and summer. Probably it does so throughout the year there, as Kramp (1924) found to be the case in the Mediterranean.

Vertical Range: No *Periphylla* were caught in hauls from 366-0 meters or shoaler. The distribution of the catches in both years combined, in the deeper hauls, was as follows:

---

[22] The smallest individuals are in poor condition, but gonads are visible in several not more than 5 mm. in diameter, though still very small.

[23] It is not likely that it will ever be found in the Red Sea, for example.

Depth in Meters.	No. of Hauls Made.	No. of Specimens.	Av. No. Specimens per Haul.
366-0	12	0	0.0
549-0	23	2	0.08
732-0	40	4	0.1
914-0	132	53	0.4
1,097-0	134	85	0.6
1,280-0	132	29	0.2
1,463-0	135	28	0.2
1,646-0	135	60	0.4
1,829-0	135	48	0.4
2,012-0	4	2	0.5

From the foregoing, it appears that in the region in question, *Periphylla* regularly lives only deeper than about 600 meters and has its chief abundance considerably deeper (from about 900 meters downward) than in the Mediterranean, or off the coast of Spain and Portugal where the *Thor* (Kramp, 1924) found it most numerous in hauls from about 150-200 to 600-700 meters[24], while one Mediterranean catch was made close to the surface. Farther north in the Atlantic, also, the upper limit to its most frequent occurrence was found to be between about 250 and 500 meters (occasional specimens as shoal as 50 meters) along the route of the *Michael Sars* Expedition (Broch, 1913); in the Sognefjord, Broch (1913) reports it as numerous as shoal as 150 meters—again with its upper limit a little above 50 meters. And in west Greenland waters the *Ingolf* found it about equally frequently at one level as at another, right up to the surface (Kramp, 1913). In high southern latitudes, also, *Periphylla* has been taken, not only in deep hauls, but in the superficial stratum, and at the surface as well, on several occasions (Browne, 1910; Stiasny, 1934, Table, p. 364, 365). The combined picture is thus of a species strictly bathypelagic throughout most of its range, but with the upper limit to its normal occurrence lying at a progressively higher level, toward high latitudes, until, in subpolar seas, it comes right up to the surface. Stiasny's (1934) observations show, too, that in upwelling regions it may frequently be brought up to the superficial strata, as well as casually elsewhere, as noted above.

So far as is yet known, it is in the Sargasso Sea region (typified by the vicinity of Bermuda) that the upper boundary to its regular occurrence lies deepest, at least for the Atlantic. On the basis of these data, it seems likely that the upper boundary for *Periphylla* is set by light combined with temperature. As to the latter, one can at least say that water of 12°-13° is not unfavorably warm for it, witness its regular occurrence in the deeps of the Mediterranean (Kramp, 1924). But, so far as I have been able to learn, it has never been found, more than casually, in temperatures much higher than that.

Recorded captures do not suggest any definite lower limit; like sundry siphonophores (Bigelow and Sears, 1937), however—and perhaps the majority of bathypelagic animals—its numbers decrease as truly abyssal depths are reached.

Segregation by sizes shows that the upper zone of concentration, near the 1,000-1,200 meter level, represents the zone of greatest abundance of juveniles, the depth distribution of specimens of 15 mm., or smaller, being as follows:

---

[24] Kramp (1924) estimates the depths of the *Thor* hauls as equalling about one-half the length of wire out. But it seems likely, from Jespersen's (1915) experiments, that the towing depths were actually somewhat greater, with 2/3 the wire length as perhaps maximal (Bigelow and Sears, 1937, p. 73).

Depth in Meters.	Number Juveniles.	Depth in Meters.	Number Juveniles.
366-0	0	1,463-0	6
549-0	4	1,646-0	18
914-0	41	1,829-0	8
1,097-0	44	2,012-0	1
1,280-0	9	2,195-0	1

The largest individuals were even more definitely concentrated in the deepest strata—responsible in part for the apparent concentration at the 1,400-1,800 meter level—for out of the 16 specimens, of 35 mm. or larger, 7 were from 1,646-0 meters[25], 8 from 1,829-0 meters, one only from a shoaler haul (549-0 meters).

It is especially interesting that in West Greenland waters, Kramp (1913) found juveniles most abundant at about 600-700 meters[26], i.e., but little shoaler than at Bermuda. This perhaps indicates that *Periphylla* is not permanently endemic in the Arctic water of the Greenland-Labrador sea region, but that the supply there is maintained by the deep indraft of Atlantic water, a hydrologic phenomenon now well recognized.

NAUSITHOIDAE.

Nausithoe.

Nausithoe punctata Kölliker.

Nausithoe punctata, Kölliker, 1853, p. 323.

For synonymy, see Bigelow, 1909, p. 35; 1928, p. 498; Mayer, 1910, p. 554; Thiel, 1928, p. 25.

Material: Net No. 627, 1,097-0 meters, May 23, 1930, 1 specimen.

Net No. 719, 1,280-0 meters, June 25, 1930, 2 specimens.

Net No. 773, 1,829-0 meters, July 4, 1930, 1 specimen.

Net No. 793, 1,280-0 meters, July 9, 1930, 1 specimen.

Net No. 967, 914-0 meters, September 30, 1930, 1 specimen.

The specimens, ranging from 5 to 9 mm. in diameter, are specifically recognizable, though fragmentary; one alone (Net No. 793) still shows the characteristic dark-pigmented ocellus on one of the rhopalia.

Earlier accounts have credited *N. punctata* with spherical gonads, as has been true of the specimens of it from the eastern tropical Pacific, from Japanese waters, from the Mediterranean, and from Florida and the West Indies that I have previously examined; likewise of the specimen from Net No. 793 (a ♀ with eggs of various sizes). A specimen from Net No. 719 and one from Net No. 967 seem at first sight to have horse-shoe shaped gonads, with concavities directed centripetally. But it appears from more careful examination that the pockets (globular in life) within which the sex products are developed, had been torn open on the centripetal sides by the rough treatment the specimens had received, correspondingly disrupting the sexual tissue still adhering to their inner walls. That is to say, their present resemblance to the horse-shoe shaped gonads pictured by Haeckel (1879, Pl. 27), for his genera, *Ephyra* and *Palephyra*[27], is purely accidental.

---

[25] This tends to corroborate Stiasny's (1934, p. 363) conclusion that, during its development, it tends to move slowly into the deeper layers.

[26] Recorded at 1,000 meters of wire out.

[27] In Vanhöffen's (1902, Pl. 3, Fig. 10) illustration of *Palephyra indica*, they are kidney-shaped.

This being a neritic species, it is likely that the specimens here listed were the product of the Bermudian Bank. To find *N. punctata* a few miles out from the land is no surprise, for it has long been known that the free-living stage of *N. punctata* endures long enough for it to drift much greater distances. It had not been recorded previously from Bermudian waters, but was to be expected there, for it is common in the West Indies (Mayer, 1910), as well as widespread in warm seas generally. See Mayer (1910, p. 555), for a summary of the earlier accounts of its developmental stages.

As the attached stage is known to be commensal within certain sponges of the littoral zone, and as adults have commonly been taken close to the surface elsewhere, it is somewhat astonishing that the Bermudian specimens were all from deep hauls. But the numbers concerned are so small that no estimation is possible of the actual depths of capture.

ATOLLIDAE.

Atolla.

Atolla wyvillei Haeckel.

Atolla wyvillei, Haeckel, 1880, p. 488; 1881, p. 113, Pl. 29, Figs. 1-9.

For early synonymy, see Mayer, 1910, p. 563, 565, 567 (*"A. bairdii"* + *"A. valdiviae"* + *"A. gigantea"* + *"A. wyvillei"*).

For subsequent discussions of relationships, see especially Broch (1913, p. 13), Browne (1916, p. 203), Bigelow (1928, p. 505), and Stiasny (1934, p. 365.).

Material: Net Nos. 23, 26, 29, 36, 39, 41, 53, 62, 66, 74, 78, 100, 102, 105, 111, 118, 122, 142, 154, 196, 221, 240, 247, 253, 292, 293, 295, 296, 368, 434, 539, 544, 545, 546, 552, 553, 556, 561, 562, 563, 565, 568, 574, 575, 582, 588, 596, 597, 598, 599, 601, 605, 606, 611, 618, 619, 625, 626, 631, 632, 633, 637, 639, 647, 648, 652, 657, 659, 666, 674, 676, 681, 682, 685, 687, 688, 691, 698, 701, 707, 719, 720, 721, 727, 739, 741, 745, 748, 767, 770, 774, 777, 778, 781, 787, 789, 798, 799, 800, 801, 804, 806, 808, 810, 812, 824, 826, 829, 831, 838, 846, 850, 860, 861, 863, 865, 875, 881, 882, 885, 892, 917, 926, 928, 937, 938, 943, 964; 549-0 to 1,829-0 meters; 232 specimens, 1-6 per haul, except for Net Nos. 565, 707, and 767, which captured 10, 8, and 9 specimens respectively. The specimens range from 7 to 100 mm. in diameter.

It now seems so thoroughly established that all known Atollas, that have smooth marginal lappets, belong to the one species *wyvillei*, that this viewpoint needs no further defence (see Kramp, 1924; Bigelow, 1928; and Stiasny, 1934, for recent pronouncements on this subject). Stiasny (1934, p. 366) has thought it possible from his study of the extensive *Discovery* series to divide the comprehensive species *wyvillei* into three forms, according as the margin of the central disc is indented with broad radial notches (*wyvillei* form), or with narrow notches (*verrillii* form), or is entirely smooth (*bairdii* form), Conditions, however, in the Bermuda series and in the others I have studied suggest that these differences (so far studied only in preserved material), like the relative prominence of the annular zone, chiefly reflect the state of contraction, or relaxation of the animal when preserved. But individual variation may also enter into the case, to a degree that it is not yet possible to estimate. Certainly, we do not have to do with geographic variation, for the *Arcturus* and *Discovery* collections have already shown that it is not unusual for narrow-notched, broad-notched, and smooth disced individuals to be taken side by side in the same haul. In a given individual some of the notches may, furthermore, be broad, others narrow (Bigelow, 1909, p. 40); and it frequently happens that a given individual may be equally well characterized as "broad-notched," or as "narrow," there being a complete inter-graduation between the two. The Bermuda collection now contributes at least one specimen (Net No. 221) about 65 mm. in diameter, in which the margin of the disc is entirely smooth on one side, but shows clear traces of broad notches on the other.

Recent collections have yielded the smooth and notched or furrowed forms in varying proportions, the relative counts being 112 notched (*verrillii, wyvillei*), and 92 smooth (*bairdii*), for the *Discovery* series (Stiasny, 1934, p. 370), 12 notched to 3 smooth, for the *Thor* series (Kramp, 1924), and 103 smooth (or nearly so) to 57 furrowed, for the *Michael Sars* collection (Broch, 1913). Among such of the Bermuda series as are in good enough condition to be significant in this respect, there are 25 smooth to 38 with the margin of the disc variously notched.

Previous collections had shown that in specimens upwards of, say, 30 mm. in total diameter, i.e., presumably with the final number of tentacles, there may be as many as 29 or as few as 14 of these; the majority of large specimens having from 22 to 28 (see Vanhöffen, 1902, Bigelow, 1909, and Kramp, 1924, for tabulations of tentacle numbers at different sizes). Eighteen to twenty-two tentacles have already been recorded in small specimens 8-10 mm. in diameter (Vanhöffen, 1902; Kramp, 1924). Among the smallest of the Bermudian specimens, of 7-12 mm., the tentacle number ranges from 19 to 24, most frequently 20, the smallest specimen (7 mm.) having the latter number.

The most interesting contribution by the Bermudian series to knowledge of *Atolla* is its confirmation of earlier observations (Maas, 1897; 1904, Vanhöffen, 1902) that the gonads regularly appear while the medusa is still very small, for these organs are already of moderate size in 11 out of 14 specimens of 7-9 mm., while all but two out of the 54 specimens of 15 mm. or smaller, that are in good enough condition for study, have gonads. And eggs of various sizes are clearly visible in one specimen of only 10 mm., in two of 11 mm., in one of 13 mm. and in one of 14 mm. But it seems that in occasional specimens these organs may not develop until much later, for in one of 30 mm., the gonads are still very small. At the other extreme, Maas (1904) has reported a 72 mm. *Atolla* as spent. Even the largest, however, of the Bermudian specimens, from 60-100 mm. in diameter, still have full, or partly full gonads, both sexes being represented.

In short, it appears that *Atolla*—like *Periphylla*—is sexually active throughout most of the growth period. But nothing is yet known as to how long, in point of time, this latter may continue.

Broch (1913) has argued, from the depth distribution of the extensive series collected by the *Michael Sars* in the North Atlantic, that the wide variations that occur in the characteristic pigmentation of *Atolla* are correlated with the depths at which given specimens live, those in which only the stomach is densely pigmented (Broch's group I) having been taken most numerously in hauls from 500 meters, those with more extensive pigmentation in hauls from 750 and 1,000 meters. Stiasny (1934) likewise found the *Discovery* captures at least compatible with this, except in the Antarctic and in the upwelling waters off West Africa. Unfortunately, the Bermudian series throws little light on this point, partly because the great majority of the hauls sampled the water to a depth of 900 meters or more, and partly, because the great majority of the specimens were so much rubbed in the nets, that it is impossible to tell how extensive their pigmentation was in life. The most that can be said is that 14 of the 16 specimens in which the ring muscle is strongly pigmented (or apparently was so in life), were from hauls from 1,097-0 meters, or deeper, whereas the genus was of most frequent occurrence in the 914-0 meter hauls, as noted below. But it is not safe to estimate the vertical distribution of the contrasting specimens in which the pigment is now confined to the stomach (Broch's group I), because many of these still show some slight trace of peripheral pigment, as well.

General Distribution: *A. wyvillei* has already been reported close to Bermuda (Bigelow, 1928, p. 509), as well as at many other localities widespread in the North Atlantic from side to side; it is in fact now known to be one of the most cosmopolitan of bathypelagic medusae, to be expected anywhere in the basins of the open oceans. But like some other bathypelagic forms, it seems to be barred from access to the Mediterranean (Kramp, 1924; Bigelow and Sears, 1937).

To the northward, it has been taken to Lat. 64° N. in the western side of the Atlantic, north of the Faroe-Shetland ridge in the eastern (Kramp, 1914; Broch, 1913), to Bering Sea in the Pacific (Bigelow, 1913). To the southward, its recorded range extends right down to the Antarctic, namely to Lat. 63° S. in the Indian Ocean (Vanhöffen, 1902): to 68° S. in the Atlantic (Stiasny, 1934), to 70° 30′ S. in the Pacific (Browne, 1910).

Seasonal Distribution: In 1930, *Atolla* was taken rather regularly right through the collecting season, from early May until late September. In 1929, however, when it occurred regularly from April through July, only one was taken in August, only 6 (in one net haul) in September, although 169 hauls to suitable depths (500-0 meters) were made during those two months. Similarly, the total number taken was only about ⅓ as great in 1929 (54 specimens) as in 1930 (171 specimens) although many more hauls were made to 900-0 meters or deeper, in the former year (462 hauls) than in the latter (343 hauls). In our present ignorance of the ecological relationships of this species, any attempt to explain this annual difference in its abundance would be pure guesswork. As elsewhere emphasized (Bigelow, 1918, p. 509) winter towing, in the Cape Hatteras-Bermuda-Bahamas triangle, did not yield it at all. But the interpretation of this seasonal periodicity must await a knowledge of whether it passes through a fixed stage in its development, or whether it is holoplanktonic as seems the more likely from its bathymetric range.

In 1929, so few very small specimens (of 12 mm. or less) were taken (3 in April, 1 in May, 1 in July, 1 in August) that no weight can be given to their seasonal distribution. In 1930, however, there was an unmistakable concentration of young stages in spring and autumn (24 were taken in May, 6 in June, 11 in September) contrasting with the comparative scarcity in July (5) and August (1). A combination of the data for the two years yields the picture of a species breeding at least from mid-spring to early August, but with a definite slackening of production in the late summer.

Vertical Range: The distribution of the specimens according to the depth of haul is as follows:

Depth in Meters.	No. of Specimens.	No. of Hauls.	Specimens. per Haul.
366-0	0	12	0.0
549-0	2	23	0.09
732-0	3	40	0.08
914-0	56	133	0.42
1,097-0	41	134	0.3
1,280-0	38	132	0.3
1,463-0	42	132	0.3
1,646-0	32	135	0.2
1,829-0	14	135	0.1
1,829-0	0	5	0.0

This indication of an upper limit not far from 500 meters, and of a preponderance between 1,000 and—perhaps—1,500 meters, is in line with the catches of the *Michael Sars* farther north in the Atlantic (Broch, 1913).

The catches of very small specimens (of 13 mm. or smaller) show even more definite concentration near the 1,000 meter level, with no indication whatever of any tendency on the part of the juveniles to live at any higher level in the water than do the adults; data are as follows:

Depth in Meters.	No. of Specimens.	No. of Hauls.	Specimens per Haul.
366-0	0	12	0.0
549-0	0	23	0.0
732-0	1	40	0.02
914-0	27	133	0.20
1,097-0	8	134	0.06
1,280-0	8	132	0.06
1,463-0	5	132	0.04
1,646-0	6	135	0.05
1,829-0	2	135	0.02

There is, however, some indication that as Atollas attain their full size they tend to sink, for no specimens of 50 mm. or larger were taken as shoal as 732-0 meters, only one from 914-0 meters, 3 at 1,097-0 meters, 2 at 1,280-0 meters, 7 at 1,463-0 meters, 6 at 1,646-0 meters (a preponderance at, say, 1,400 meters or deeper), and one at 1,829-0 meters.

LINUCHIDAE.

Linuche.

Linuche unguiculata Schwartz.

Medusa unguiculata, Schwartz, 1788, p. 195, Pl. 6, Fig. 1.

For synonymy, see Mayer, 1910, p. 558 (*"L. unguiculata"*), p. 560 (*"L. aquila"*); Vanhöffen, 1913, p. 429; Bigelow, 1928, p. 510; Stiasny, 1931, p. 30, 1935, p. 13; Darby, 1933, p. 268.

Material: Dip-net, surface, June 8, 1929, hundreds of specimens, about 1.5 mm. in diameter.

Dip-net, surface, July 23, 1929, 1 specimen, 5 mm. in diameter.

Net No. 293, 1,280-0 meters, July 12, 1930, 1 specimen, 6.5 mm. in diameter.

Net No. 690, 2,012-0 meters, June 9, 1930, 2 specimens, 4.5-11 mm. in diameter.

Net No. 694, 1,646-0 meters, June 12, 1930, 1 specimen, 5.5 mm. in diameter.

Reasons are given in an earlier paper (Bigelow, 1928) for including, under the old name *unguiculata,* the form *aquila,* first described by Haeckel (1880), which has at various times been regarded as a distinct Pacific species, or as a variety sufficiently well marked to deserve recognition in nomenclature. And this union has subsequently been accepted by Stiasny (1931).

Thiel (1928) has argued that *L. draco* Haeckel is a distinct species, separated from *unguiculata* by its large size (up to 20 mm. in diameter), by the arrangement of the subumbral pockets in two series, by the number

(48) of horse-shoe shaped gonads, and by green color (due to the infesting zooxanthellae). It is doubtful, however, whether these distinctions will stand the test of time. Size, in particular, is hardly likely to prove of specific significance. At most, a large variety might be indicated—whether regional, or seasonal—or representing the growth of the members of a particular brood under specially favorable surroundings. So far as the number of pockets and their arrangement is concerned, I may point out that while it is usual in typical *unguiculata* for these to be in 3 rows, 32 in the outer, 16 in the median, 4-8 in the inner, an occasional large specimen (12 mm.) may lack the inner row entirely. And the number in the intermediate row may even be as small as 8, reducing the total number to 40 (Bigelow, 1928, p. 512, Fig. 184). It has also been found in typical *unguiculata* that, while the gonads originate in pairs, the members of each pair may, with growth, either "come together in the perradii, resulting in four horse-shoe shaped figures" (Bigelow, 1928, p. 513, Fig. 184); i.e., attain the *"draco"* condition, or may still continue separate until the medusa is well grown (Bigelow, 1928, p. 513, Fig. 183).

Nor does color seem any more likely to prove an alternative character, Darby (1933) having recently found that *L. unguiculata,* at the Tortugas, contains 2 pigments[28], which—depending on the degree of oxidation—give the subumbrella a yellowish brown color by day (the usual *unguiculata* color), but a spotted dark green pattern by night, i.e., the *"draco"* hue. In short, it now seems probable that specimens having the *"draco"* characteristics, represent variants of *unguiculata,* though we are still entirely in the dark, as what conditions—seasonal, environmental, or genetic—favor their appearance.

General Distribution: Previous records for the general region of Bermuda (Fewkes, 1883; Bigelow, 1928) had already made it likely that the Bermuda Bank is a center of production for *Linuche,* the farthest extra-tropical such center in the Atlantic. And this is corroborated by the catch of juveniles, listed above.

Vertical Range: *Linuche* commonly swarms at the surface. The few specimens listed above from deep hauls were probably picked up by the nets on their way down or up.

DISCOPHORA.

PELAGIDAE.

Pelagia.

Pelagia noctiluca Forskål.

Medusa noctiluca, Forskål, 1775, p. 109.

For synonymy, see Mayer, 1910, p. 572-576 (*"P. noctiluca," "P. noctiluca* var. *neglecta," "P. cyanella," "P. panopyra," "P. panopyra* var. *placenta," "P. flaveola," "P. perla," "P. phosphora," "P. crassa,"*); Stiasny, 1914, p. 529, p. 531 (*"P. purpuroviolacea"* and *"P. rosea"*); 1924, p. 83 (*"P. curaçaoensis"*).

Material: Net No. 863, 1,646-0 meters, September 8, 1930, 1 specimen, about 26 mm. in diameter.

Surface, September 12, 1930, 1 specimen, about 45 mm. in diameter.

The several authors who have recently studied this wide-ranging and widely varying genus, have successively reduced the number of so-called species. On the basis of the *Arcturus* collection, I concluded that one species of *Pelagia* (*P. noctiluca*), at any rate, "occurs widespread, over the warmer parts of the Indian and Pacific and Atlantic oceans" (Bigelow, 1928, p. 519) and doubted whether any of the other named forms could be separated from it, specifically. Stiasny (1934, p. 388), in his most recent discussion of the genus, likewise makes equally drastic reduction, writing "there is most probably only a single species of *Pelagia* with a world wide distribution over all tropical and subtropical parts of the ocean." This species must bear the name that was earliest given to a medusa recognizable as *Pelagia*, the *P. noctiluca* of Forskål. Menon (1930) has likewise applied this name, without discussion, to *Pelagia* from the Indian Ocean.

---

[28] Probably these are actually in the contained zooxanthellae.

Subsequently, however, Stiasny (1935) has maintained that *flaveola* is also a good species.

Whether any of the other named forms deserve recognition at all, as geographic or environmental races, or whether they merely represent individual or swarm variations, different stages in growth, or contraction phases, is still an open question, the solution of which is not aided by the present small series. I can only point out that, in the larger specimen, linear exumbral warts greatly predominate in the marginal zone, but are intermingled with round-oval warts in nearly equal numbers in the central zone. That is to say, the so-called *perla* and *pelagia* types are combined with the *noctiluca* type (narrow linear warts) on different parts of the bell. Menon (1930) also reports finding both long warts and rounded. This is additional evidence that specific distinctions cannot be based on the shape of these structures.

General Distribution: *Pelagia* was to be expected in the collection, having already been found near Bermuda (Fewkes, 1883; Bigelow, 1928). It is, however, interesting that so large a number of hauls, shoal as well as deep, made in so many different months, should have yielded so few specimens of a species which has now been encountered—often in swarms—at many stations, in the warm belts of all oceans, as well as in the Mediterranean.

Poralia.

? **Poralia rufescens** Vanhöffen.

Poralia rufescens, Vanhöffen, 1902, p. 41, Pl. 4, Fig. 15, 16; Bigelow, 1909, p. 45, Pl. 13, Figs. 1-5.

Material: Net Nos. 50, 247, and 726; hauls from 1,646-0, 1,829-0, and 1,463-0 meters; fragments of the central parts of 3 specimens; diameters of base of stomach, respectively about 30, about 35, and about 18 mm.

This species is one of the most interesting finds in the collection, for it is only the third record for the genus. *Poralia* was first described by Vanhöffen (1902) for a fragmentary specimen (marginal zone torn off) with very simple gonads consisting of outpocketings projecting direct from the gastric wall into the subumbral cavity, in seven groups of 3 or 4 pockets each. This type of symmetry, as Vanhöffen pointed out, was previously known (for Scyphomedusae) only as an abnormality of *Aurelia*. There were 21 or 22 narrow radial canals.

Two specimens in the *Albatross* collection (Bigelow, 1909), though likewise very fragmentary, allowed some amplification of Vanhöffen's original account. In the smaller, there were 8 groups of sexual folds, and 21 canals in about ½ the circumference, suggesting octoradial arrangement and about twice as many canals as Vanhöffen's example. In the larger and somewhat better preserved *Albatross* specimen, about 250 mm. in diameter, the sexual folds formed a practically continuous ring, surrounding the base of the stomach, but separated by gelatinous pillars, into 18 or 19 groups of 6 or 7 pockets each. And there were 41 canals. As already remarked (Bigelow, 1909, p. 46), a growth series is here indicated, with multiplication of canals, and of sex folds, accompanied by a corresponding formation of additional pillars.

In the largest Bermudian specimen (so far as can be seen in the present fragmentary state), the sex folds are in five groups, separated by as many broad gelatinous pillars, corresponding to as many angles at the base of the manubrium. The number of folds per group is 5, 5, 6, 5(?), 5, while in most of the groups the larger central folds are flanked in addition by indications of very small folds, which (if they developed) would raise the number per group to 6-8. Several of the folds contain large eggs. But this cannot be taken as proof that the specimen had reached its full growth, for it is equally possible that the development of sex products may extend over a considerable period, allowing opportunity for subdivision of the primary groups of six folds by the development of additional pillars. The number of pillars is also apparently five in the smallest specimen (stomach, 18 mm. in diameter); the condition of the third specimen is too bad for counting.

The canals are very narrow, as in Vanhöffen's example of corresponding size, approximately 38 in number in the smallest specimen, about 40 in the example 30 mm. in diameter of stomach, but only about 30 in number in the largest.

These conditions of metamerism in the Bermudian specimens make it likely, not that *Poralia* is primarily octoradial as I formerly suggested, but that it is primarily quadriradial, but that with the growth of the medusa, the original state is obscured by the formation of additional canals, and by subdivision of the original groups of sex folds through the development of additional gelatinous pillars. Different specimens would then show different numbers of groups of sex folds—as is actually the case—if these developments take place at different rates, in different radial sectors, as may very well happen. Decision whether geographical races of the species exist in this respect, or whether it has been a matter of pure chance that different numerical conditions have been illustrated by the few specimns so far seen from the Indian, Pacific, and Atlantic oceans, must await a study of larger series.

In the Bermudian, as in the *Albatross* examples (Bigelow, 1909, Pl. 13, Figs. 1-3), the gastric cirri are arranged in a single fringe-like row, in as many groups as there are groups of sex folds, there being none on the gelatinous pillars.

Nothing can be said as to the form of the manubrium, all but the base having been destroyed.

The marginal zones have been torn off, as was also the case in Vanhöffen's and in the smaller of the *Albatross* specimens. And while the larger of the latter showed the distal terminations of the canals, and allowed a description of the rhopalia, the tentacles of this genus have yet to be seen.

The Bermudian specimens, like those previously seen, show the bathypelagic type of pigmentation, for they are given a reddish chocolate hue by pigment granules so large as to be individually visible under a magnification of only 3 diameters. Even the gelatinous substance is sparsely pigmented throughout; such of the subumbrella surface as is intact more densely so, likewise the surface of the sexual folds, though in places where the latter are torn, allowing the eggs to show through (specimen from Net No. 247), these are opaque white, as is also the case in *Aeginura*.

The depths of capture, listed above, added to preexisting records of 1,100-0 meters (Vanhöffen, 1902) and 549-0 meters (Bigelow, 1909), combined with the fact that a form so easily recognizable, and so striking in appearance has been taken on only 3 occasions, is sufficient proof that its habitat is exclusively bathypelagic.

AURELLIIDAE.

Aurellia.[29]

The written history of *Aurellia* extends back nearly two centuries, during which period many descriptions of its members have appeared, and discussion of their interrelationships. It has been the object of much investigation, embryologic, physiologic, and varietal; and it is commonly used as material for biological teaching. None the less, we still await critical revision of the seventeen "species" of *Aurellia* that have been named.

It is, however, generally accepted that most of these represent nothing more than contraction-phases, growth stages, individual variants, or at most environmental races of a much smaller number. Thus, Mayer (1910, p. 620, 622), in his tabular view of the genus, grouped all the named forms as either "*aurita* and its varieties" or "*labiata* and its varieties." Comparison, a few years later, between specimens of the *aurita* group from various Atlantic and Pacific localities, lead me to the conclusion that they are not separable into varieties, by any of the characters previously suggested (Bigelow, 1913, p. 98). And Stiasny (1919a; 1922, p. 524, 525), after a preliminary survey of the genus, concluded that all known Aurellias fall in one or another of four "wohlunterscheidbare grüppen, nicht Varietaten" of the "grossen Species *aurita*" characterized by differences in the number of canals arising from each genital sinus.

The difficulty in defining the forms of *Aurellia* (whatever be the taxonomic rank of these) lies in the fact that the character chiefly involved, in recent discussions, is one in which differences are gradual, not discontinuous, namely, the complexity of branching of the canals, and the extent to which the branches anastomose. The extremes in this respect are far apart. The one is represented by the simple state illustrated by Mayer (1910, p. 624, Fig. 397) for a Mediterranean example, in which the main perradial canals show no branching between the subdivision that takes place close to their points of origin, and the immediate vicinity of the bell margin, and in which anastomosis is also confined to the latter region. The other extreme is represented by the form first reported by Brandt (1838) from Kamchatka, and subsequently by Uchida (1934) and by me (1913; 1920) from northern Japan, from the Sea of Okhotsk, and from the Bering Sea-Alaska region, in which the perradials give off numerous branches throughout the outer ⅓ of their lengths, and in which there is any extensive anastomosis between all the primary systems, perradial, interradial, and adradial. I have already argued (Bigelow, 1913; 1920) that this form differs so sharply from typical *aurita* in this respect, (also in the dense pigmentation of the margin) as to deserve specific recognition as *A. limbata* Brandt. However, it proves that the further difference reported by Uchida (1934), namely wrinkled exumbral sense pits in *limbata,* smooth in *aurita,* is not a dependable specific character (unless perhaps for full-grown specimens), for while the pits in a large example from the Kurile Islands agreed with Uchida's description in their wrinkling (Bigelow, 1913, p. 100, Pl. 5, Fig. 2), they are smooth in the smaller specimens with *limbata* canalization that I have seen. Neither have I been able to demonstrate, on any of the Aurellias of this type, the partial closure of the mouth by flaps from the oral arms, reported by Uchida (1934) and thought by him to suggest rhizostome affinities. This perhaps represents a contraction phase.

Aurellia limbata, in short, is very closely allied to *aurita* though differing enough from the latter (at least in its typical form) for specific recognition. It also has a much more circumscribed range, for all records of Aurellias, the canals of which have shown the extreme complexity and extensive anastomosis characteristic of *limbata* have (so far as I am aware) been from the Arctic or Subarctic; namely, from northern Japan, Kamchatka, Sea of Okhotsk, the Bering Sea region (Brandt, 1838; Uchida, 1934; Bigelow, 1913; 1920), and Greenland (Kramp, 1913, as "*A. flavidula*"). Thus it is circumpolar, as I have previously pointed out (Bigelow, 1920, p. 14).

---

[29] This name has usually been spelled *Aurelia.* But Peron and Lesueur's (1809) original spelling was *Aurellia,* as Mayer (1910, p. 619) points out.

The status of *A. maldivensis* Bigelow, and of *A. solida* Browne—the former recently redescribed by Stiasny (1935), the latter by Menon (1930) and by Rao (1931)—still remains uncertain.

Aurellia aurita Linné.

Medusa aurita, Linné, 1758, p. 660.

For early synonymy, see "*A. aurita,*" Mayer, 1910, p. 623, 627, and "*A. labiata,*" p. 628.

The more important subsequent discussions are listed above (p. 167).

Material: Net No. 296, 1,829-0 meters, July 12, 1929, 1 specimen, about 85 mm. in diameter.

Dip Net, Surface, October 16, 1930, 10 specimens, about 30-80 mm. in diameter.

Net No. 880, 914-0 meters, September 12, 1930, 1 specimen, fragmentary, about 85 mm. in diameter.

Also, 9 other Bermuda specimens, 25-90 mm. in diameter in the collection of the Museum of Comparative Zoology, collected in the summers of 1902, 1903, 1916, 1917.

The number of canal roots, arising from each genital sinus, shows the following range, in specimens of different sizes:

Diameter in mm.	Number of Specimens.	Number of Canals per Sinus.
25	2	3
30	1	3
33	1	3-4
35	1	3
37	1	3
40	2	3
45	1	3
50	1	3-4
52	1	3
55	1	1-3
75	2	3-5
80	2	3-5
90	1	4-5

Thus, most of the smaller examples would fall in the "*aurita*" group, according to Stiasny's (1922) subdivision, while the larger specimens bridge the gap between the latter and his "*colpota*" group. The first branching of the primary interradial canals is trichotomous, as Stiasny (1922) has emphasized, with further branching leading to the formation of what Mayer (1910, p. 624) has aptly named a "pitchfork-shaped system." In small Aurellias, the first branching of the interradial canals usually lies some distance distal to the boundary of each genital sinus. It is, in fact, probable that all Aurellias pass through this "*aurita*" stage in this respect, when they are small. The outer boundaries of the sinuses spread centrifugally with growth. And it appears that the number of separate trunks that arise from a given sinus, in larger individuals, depends chiefly in how far outward the canal-system has become incorporated into the sinus, by the growth of the latter. With *Aurellia* proverbially variable and subject to abnormality, it is not astonishing that the number of canals often differs for the different sinuses of a given individual.

The Bermudian series gives evidence, in the foregoing tabulation, of the tendency toward an irregular increase in the number of canals, with growth, that is to be expected, on this basis. Failure of any of the specimens[30] to show a larger number of canal-roots than 5 per sinus is no doubt due to the fact that none of them was of large size. For example, the numbers per sinus in a large Cuban specimen, 250 mm. in diameter, are 6, 6, 8, 7.

I may note, in passing, that anastomosis of canals in the Bermudian specimens, is much as it has frequently been described for *A. aurita.*

General Distribution: It has long been known that *A. aurita* is one of the most abundant of medusae among the West Indies, and northward from Florida along the east coast of North America. It is also a familiar object at Bermuda, although no printed record of its presence seems to have appeared. Being strictly a neritic form, the specimens in the present collection were no doubt the product of the Bermuda Bank.

FAUNISTIC CONSIDERATIONS.

Neritic and Holoplanktonic Communities.

It is safe to conclude—from the geographic location of the station where the towing was done—that all the medusae taken, of species that pass through a fixed stage in their development, were the products of Bermuda. Hence, a comparison of this neritic element, in the catches, with the holoplanktonic species gives a good indication of the extent to which a small isolated Bank may be expected to contribute to the medusan fauna of the open ocean nearby.

In the case of the Hydromedusae, out of a total of 717 specimens, the number belonging to species that are either known to pass through an attached hydroid stage, or may reasonably be assumed to do so,[31] does not exceed 17. This, I may point out, does not include the small series of *Bougainvillia niobe,* which has a budding phase, hence is placed in the holoplanktonic category, so far as its dispersal is concerned. That is to say, the contribution made by the neighboring slopes and shallows of Bermuda, to a point not ten miles distant, was less than 3% of the total catch. And the numerical paucity of the neritic element is the more striking, when one recalls that it represents at least 9 species, the holoplanktonic element (Tracho- and Narcomedusae) only 14. It is probable that if the station had been located but a few miles further offshore, the neritic element in the medusa fauna would have been negligible, as Thiel (1935) has shown it to be for the Central and South Atlantic as a whole.

In the case of the Scyphomedusae, the situation was the reverse, if judged from the standpoint of total numbers only, for the number of neritic specimens was raised considerably above that of the holoplanktonic by one catch of several hundreds of juveniles of *Linuche,* a genus which almost certainly passes through a scyphistoma stage, though not yet actually proven to do so. And a second large catch (66) was also made of *Carybdea xaymacana,* which also probably has a polyp stage in coastal waters. However, if the neritic and holoplanktonic groups of Scyphomedusae be judged, not by numbers of specimens, but by the frequency of occurrence, the latter group ranks far in advance, for 252 hauls yielded representatives of genera certainly or probably holoplanktonic (*Atolla, Periphylla, Pelagia*), while only 16 hauls and surface collections yielded genera which may be safely called neritic (*Carybdea, Tamoya, Nausithoe, Linuche, Aurellia*). And apart from the two species just mentioned, neritic (or probably neritic) Scyphomedusae numbered only 23 specimens, holoplanktonic Scyphomedusae 549.

---

[30] Except for two abnormal tripartite specimens, each about 80 mm. in diameter, in which the number of canals per sinus were 9, 7, 9, and 9, 6, 7.

[31] *Zancleopsis, Pandea, Heterotiara, Calycopsis, Chromatonema, Aequorea, Olindias.*

Apart, then, from sporadic contributions of 2 species, produced on the Bermuda Bank, the regular population was as characteristically holoplanktonic for the Scyphomedusae as for the Hydromedusae. Why it is that the young of *Linuche* and *Carybdea* drift offshore more frequently, or in greater numbers, than do other medusae produced on the Bermuda Bank, is a problem for the future.

VERTICAL DISTRIBUTION OF MEDUSAE AS A WHOLE.

If we omit the few specimens, for which depth data are not available; fragments which may not have represented individual medusae; and also the swarm of juvenile *Linuche*, mentioned above, the distribution of all the medusae combined with respect to depth of haul, was as follows:

Depth in Meters.	Number of Hauls Made.	Number of Medusae Taken.	Specimens per Haul.
0	86	126	1.5
183-0	10	0	0
366-0	12	0	0
549-0	23	10	0.43
732-0	40	18	0.45
914-0	132	189	1.44
1,097-0	134	246	1.83
1,280-0	132	245	1.85
1,463-0	132	235	1.79
1,646-0	135	234	1.73
1,829-0	135	220	1.63
2,012-0	4	21	5.25

The fact that the yields of 85 hauls at depths of 183-0 to 732-0 meters was so trifling, is good evidence that catches made in the deeper hauls can have owed very little, if anything, to what the nets picked up while being lowered and hauled up again. Consequently, the tabulation indicates that, numerically, the immediate surface, on the one hand, and a stratum from about the 900 meter level downward, were about equally populated, but that the intervening zone, some 700 meters thick, was practically barren. And omission of the neritic specimens from the surface catches, shows that this barren zone extended right up to the surface, for only 4 specimens of the holoplanktonic group were taken at the surface, namely, 1 *Liriope*, 1 *Halicreas*, and 2 *Aegina*.

Consideration of the comparative regularity of occurrence at different depths leads to a similar conclusion, as appears from the following tabulation:

Depth in Meters.	Number of Hauls Made.	Number with Medusae.	% with Medusae.
0	86	10 (3)	11 (.3)
183-0	10	0	0
366-0	12	0	0
546-0	23	4	17
732-0	40	12	30
914-0	132	55	41
1,097-0	134	67	50
1,280-0	132	66	50
1,463-0	132	64	49
1,646-0	135	71	52
1,829-0	135	61	45
2,012-0	4	4	100

By this criterion, for all medusae combined, and even including the swarms of juvenile *Linuche,* the medusae occurred less regularly at the surface than from about 600-0 meters downward, not at all in the intervening strata. And omission of the neritic forms lowers the surface frequency to a very small fraction of that of the deep layers, for only 3 out of the 86 surface hauls yielded holoplanktonic medusae (about 3%), or 1 for 28 hauls.

If the foregoing tabulations were taken at face value, they would suggest that medusae were about equally abundant and equally frequent from about 800 meters, or thereabouts, downward, with a decided maximum as deep as 2,000 meters. But consideration of the method by which the hauls were made shows that such a conclusion would almost certainly be incorrect, because the catches from the deepest hauls were no doubt augmented, both in frequency and in numerical yield, by what the nets picked up as they were lowered through the comparatively rich 500-800 meter stratum, and then hauled up through it again. The data are not of a sort to allow numerical calculation of the probable contamination resulting from this. But it may be safely assumed that with depth, below, say, 800 meters, this increased significantly and rapidly. And it is not unlikely that all the specimens yielded by the 4 hauls at 2,012-0 meters actually came from much smaller depths. In short, the data yields no positive evidence that there were any medusae as deep as this.

Reasoning then from the collections actually made at Dr. Beebe's station, it seems safe to conclude for the part of the Sargasso Sea represented by the Bermuda region:

1. That the neritic element among the Hydromedusae is numerically negligible; and that this also applies to the Scyphomedusae, except on occasions when swarms of one species or another may drift out for a few miles from the Bermuda Bank.

2. That the whole upper 500 meters of water is practically barren of medusae from spring, through summer, to autumn, except when such events take place. On these occasions, the immediate surface may be the most thickly populated zone. But it appears that these periods are of brief duration; nor is it likely that they affect the situation on a broad scale more than a few miles out from Bermuda.

3. That medusae as a whole in this part of the ocean basin are usually most abundant and occur most regularly at about 500-800 meters, below which they decrease, in both these respects, with increasing depth.

RELATIVE ABUNDANCE OF DIFFERENT SPECIES.

The relative abundance of the several species is shown in the following table:

Species.	Number.	Species.	Number.
Zancleopsis dichotoma	1	*Liriope tetraphylla*	1
Bougainvillia niobe	7	*Geryonia proboscidalis*	3
Pandea conica	1	*Cunina* sp?	1
Pandea rubra	4	*Solmissus incisa*	13
Heterotiara anonyma	2	*Aegina citrea*	31
Calycopsis sp?	2	*Aeginura grimaldii*	201
Chromatonema rubrum	2	? *Pegantha clara*	7
Aequorea floridana	2	*Carybdea xaymacana*	105
Olindias tenuis	3	*Carybdea alata*	3
Rhopalonema velatum	39	*Tamoya haplonema*	1
Pantachogon haeckeli	65	*Periphylla hyacinthina*	317
Colobonema typicum	47	*Nausithoe punctata*	6
? *Crossota brunnea*	50	*Atolla wyvillei*	232
Trachynemidae?	51	*Linuche unguiculata*	many
Halicreas minimum	186	*Pelagia noctiluca*	2
Halicreas glabrum	66	*Poralia rufescens*	3
Halitrephes valdivii	19	*Aurellia aurita*	12

ABSOLUTE ABUNDANCE.

Some estimate of the absolute abundance has proved interesting. Since the neritic forms may be regarded as sporadic invaders of the offshore waters, they may be left out of account in this connection. The number of holoplanktonic medusae of all kinds taken in the hauls from 549-0 meters and deeper, i.e., in the most productive zone, was about 1,406; the number of hauls 869; the number of hours of towing was 3,276; or an average yield of only 1.6 specimens per tow, or 0.42 specimen per hour's towing. Divided into groups, the catch was approximately 0.23 Trachomedusae and Narcomedusae combined, and 0.16 of the bathypelagic Scyphomedusae (*Atolla* and *Periphylla*) per towing hour.

QUANTITATIVE COMPARISON WITH OTHER REGIONS.

A quantitative comparison of the medusa population of the Bermuda region with that of the Mediterranean and of the Central and South Atlantic is interesting, as an indication of how the former—and its part of the Sargasso Sea as a whole—ranks as to productivity for this group, at different levels in the water, compared with other seas. Calculation of the Mediterranean catches made by the *Thor* as listed by Kramp (1924), but omitting one large catch of "many thousands" of *Liriope eurybia* in the Sea of Marmora (*Thor* Sta. 175, Kramp, 1924, p. 32), shows an average catch per hour's towing of about 41.5 medusae of all sorts, of about 36-37 Trachomedusae and Narcomedusae combined, and about 2.5 Scyphomedusae. Since the *Thor* collections were made with a net with a mouth area of 3 square meters, towing at a rate of about 2 sea miles an hour, the Bermudian collection with one of only about 0.78 square meters, towed at a rate of 2-2½ knots, a factor of about 3.8 must be introduced to make the catches comparable. So adjusted, it is obvious that the Mediterranean was many times the more productive region, both for the holoplanktonic Hydromedusae, and for the medusae as a whole. In the case of the bathypelagic Schyphomedusae, however—represented at Bermuda chiefly by *Atolla* and *Periphylla*, but in the Mediterranean by the latter only—the two regions were about equally rich.

The Bermudian region is also poor in the holoplanktonic Hydromedusae, in general, as compared to the Central and South Atlantic as a whole, where the *Meteor* tows, with nets only half as large in diameter, yielded an average of about 5.4 specimens per 200 meters of towing at all depths and stations combined—a number that must be multiplied by a factor of perhaps 1.8 to correct for the size of the net alone, to be made comparable with the Bermuda average catch of only 0.23 per hour's towing. And the Atlantic figure would be much increased if the vertical *Meteor* tows were to be calculated on an hourly basis.

Reference to the foregoing discussion of vertical distribution (p. 170) makes it clear that this relative poverty of the Bermuda region results chiefly from the barrenness there of the upper 500 meters of water, in holoplanktonic medusae of any sort. In the Mediterranean, by contrast, most of the hauls from the upper 100 meters of water yielded considerable numbers of medusae, of one species or another (see Kramp's, 1924 lists), while most of the larger catches of the species most plentiful there, namely *Rhopalonema velatum* and *Liriope,* were from depths no greater than 300 meters. In the Central and South Atlantic also, the *Meteor* found Tracho- and Narcomedusae most abundant (10-11 individuals per 200 meters tow) between the surface and 200 meters, much less so in the deep underlying waters (Thiel, 1935, p. 43, Fig. 20, Table 3). And evidence in the same direction, in the Pacific, results from the rich catches of medusae of this category made in the Humboldt Current off northwestern South America, by the *Albatross* (Bigelow, 1909).

From the foregoing, it appears that the very warm superficial stratum of the Sargasso Sea is notably barren of medusae of the holoplanktonic category, but so far as the evidence goes, it suggests that the productivity of the deep waters in the more strictly bathypelagic types, represented by *Periphylla* and *Atolla,* is much more nearly of the same general order of magnitude there, as it is over the ocean basins as a whole[32], or in the Mediterranean.

It is interesting as illustrating the relative numerical abundance of two allied groups of pelagic coelenterates that the average Mediterranean catch of about 41 medusae per hour's towing mentioned above (p. 172), contrasts with a corresponding average of between 200 and 300 calycophorid siphonophores, both in the Mediterranean and in the neighboring parts of the Atlantic (Bigelow and Sears, 1937, p. 137). Evidently, the latter group is much the more numerous in that particular region. But it is doubtful how far regionally this generalization would apply, for the average *Meteor* catches per 200 meters of towing, of siphonophores and of Tracho- plus Narcomedusae, for the Central and South Atlantic did not differ greatly one from the other (cf. Leloup and Hentschel, 1935, p. 24, Fig. 17 with Thiel, 1935, p. 43, Fig. 20, Table 3).

In the Bermuda region, we have no direct comparison between the two groups, as there are no published records of siphonophores for the years 1929-1930, and as the numbers captured are not recorded for the one year on record (1931, Totton, 1936). We may, however, point out that they were only taken in 55 out of 374 hauls (usually only one species in a haul), or 14% of the tows in 1931, whereas the medusae were taken at 41% of all hauls in the summers of 1929-1930. Hence assuming that the several summers were comparable, it appears that medusae are actually more frequently encountered in the Bermuda region than siphonophores. And this area may thus prove to be as barren of the latter as the former.

---

[32] Compare, for example, the catches of *Atolla* and *Periphylla* made in the North Atlantic by the *Michael Sars* (Broch, 1913).

BIBLIOGRAPHY.

AGASSIZ, ALEXANDER.

1865 North American Acalephae. *Mem. Mus. Comp. Zool.*, Vol. 1, No. 2, pp. 1-234, 360 figs.

AGASSIZ, A., and MAYER, A. G.

1902 Reports on the Scientific Results of the Expedition to the Tropical Pacific, 1899-1900. III. Medusae. *Mem. Mus. Comp. Zool.*, Vol. 26, pp. 139-176, 14 pls.

AGASSIZ, LOUIS

1860 Contributions to the Natural History of the United States. Vol. 3, 11+301+26 pp., 19 pls. Boston.

1862 Contributions to the Natural History of the United States. Vol. 4, 8+380+12 pp., Pls. 20-35. Boston.

BEEBE, WLLIAM

1931 Bermuda Oceanographic Expeditions 1929-1930. *Zoologica*, New York Zool. Soc., Vol. 13, Nos. 1-2, pp. 1-36.

BERGER, E. W.

1898 The Histological Structure of the Eyes of Cubomedusae. *J. Comp. Neur.*, Vol. 8, pp. 223-230, 5 text-figs.

1900 Physiology and Histology of the Cubomedusae. *Mem. Biol. Lab., Johns Hopkins Univ.*, Vol. 4, No. 4, 84 pp., 3 pls.

BIGELOW, H. B.

1909 Reports on the Scientific Results of the Expedition to the Eastern Tropical Pacific, 1904-1905. XVI. The Medusae. *Mem. Mus. Comp. Zool.*, Vol. 37, 243 pp., 48 pls.

1913 Medusae and Siphonophorae collected by the U. S. Fisheries Steamer "Albatross" in the Northwestern Pacific, 1906. *Proc. U. S. Nat. Mus.*, Vol. 44, pp. 1-119, Pls. 1-6.

1918 Some Medusae and Siphonophorae from the Western Atlantic. *Bull. Mus. Comp. Zool.*, Vol. 62, pp. 365-442, 8 pls.

1919 Hydromedusae, Siphonophores and Ctenophores of the "Albatross" Philippine Expedition. *U. S. Nat. Mus. Bull.* 100, Vol. 1, Pt. 5, pp. 279-362, Pls. 39-43.

1920 Medusae and Ctenophora. Rept. *Canadian Arctic Exped.*, 1913-1918. Vol. 8, Pt. H, 22 pp., 2 pls.

1928 Scyphomedusae from the Arcturus Oceanographic Expedition. *Zoologica*, New York Zool. Soc., Vol. 8, pp. 495-524.

BIGELOW, H. B., and LESLIE, MAURINE.

1930 Reconnaissance of the waters and plankton of Monterey Bay, July 1928. *Bull. Mus. Comp. Zool.*, Vol. 70, p. 429-581.

BIGELOW, H. B., and SEARS, MARY.

1937 Siphonophorae. *Rept. Danish Oceangr. Exped.*, 1908-1910, *to the Mediterranean and adjacent seas*, Vol. 2, *Biol.*, Pt. 2, H. 2, 144 pp., 83 figs.

BIGELOW, R. P.

1909 A New Narcomedusa from the North Atlantic. *Biol. Bull.*, Vol. 16, pp. 80-82.

BLAINVILLE, H. M. D. DE.

1834 Manuel d'Actinologie ou de Zoophytologie. Paris, 8+688+12 pp., Atlas of 100 pls.

BOONE, LEE.

1933 Coelenterata. Sci. Results of Cruises of the Yachts "Eagle" and "Ara," 1921-1928 . . . *Bull. Vanderbilt Marine Mus., Huntington, N. Y.*, Vol. 4, pp. 27-68, Pls. 1-24.

BRANDT, J. F.

1838 Ausführliche Beschreibung der von C. H. Mertens auf seiner Weltumsegelung beobachteten Schirmquallen . . . *Mem. Acad. Imp. Sci. St. Petersburg.* Ser. 6, Vol. 4, pp. 237-411, Pls. 1-31.

Broch, Hj.

1913 Scyphomedusae from the "Michael Sars" North Atlantic Expedition 1910. *Rept. Sci. Res. of the "Michael Sars" North Atlantic Deep Sea Expedition* 1910 . . . Vol. 3, Pt. 1, *Zool.*, 23 pp. 1 pl., 12 text-figs.

1924 Hydroida, in Kükenthal und Krumbach, Handbuch der Zool., Vol. 1, pp. 422-458.

1924 Trachylina, Ibid, pp. 459-484.

1929 Craspedote Medusen. Pt. 2. Trachylinen (Trachymedusen und Narcomedusen). *Nordisches Plankton, Zool.* Vol. 6: *Coelenterata*, pp. 481-540, Figs. 1-40.

Brooks, W. K.

1882 List of Medusae found at Beaufort, N. C., during the summers of 1880 and 1881. *Studies Biol. Lab.*, Johns Hopkins Univ., Vol. 2, pp. 135-146.

1895 The Sensory Clubs or Cordyli of Laodice. *Journ. Morph.*, Vol. 10, pp. 287-304, Pl. 17.

Browne, E. E.

1905 Report on the Medusae (Hydromedusae, Scyphomedusae, and Ctenophora) collected by Professor Herdman at Ceylon in 1902. Suppl. Rep. XXVII, *Ceylon Pearl Oyster Fisheries*, publ. Roy. Soc. London, Pt. IV. pp. 131-166, 4 pls.

1906 Biscayan Plankton. Part IX. The Medusae. *Trans. Linn. Soc., London*, Vol. 10, pp. 163-187, Pl. 13.

1910 Coelenterata. V. Medusae. *Nat. Antarctic Exped., Nat. Hist.*, Vol. 5, 62 pp. 7 pls.

1916 The Percy Sladen Trust Expedition to the Indian Ocean 1905 . . . IV. Medusae from the Indian Ocean. *Trans. Linn. Soc., London*, Vol. 17, pp. 169-209, Pl. 39.

1927 Report on the Medusae. Cambridge Exped. to the Suez Canal, 1924. *Trans. Zool. Soc., London*, Vol. 22, pp. 105-115.

Chamisso, A. de, and Eysenhardt, C. G.

1821 De animalibus quibusdam e Classe Vermium Linneana . . . *Nova Acta*, Fasc. 2. *Acad. Caes. Leop.*, Vol. 10, pp. 343-374, Pls. 24-33.

Claus, C.

1878 Ueber Charybdea marsupialis. *Arb. Zool. Inst. Wien*, Vol. 1, pp. 1-56 or (221)-(276), 5 pls.

Conant, F. S.

1897 Notes on the Cubomedusae. *Johns Hopkins Univ. Circ.*, Vol. 17, No. 132, p. 8-10, Figs. 8-9.

1898 The Cubomedusae. *Mem. Biol. Lab., Johns Hopkins Univ.*, Vol. 4, No. 1, 61 pp., 8 pls.

Darby, H. H.

1933 Studies on Pigments of Linuche unguiculata (Eschscholtz). *Carnegie Inst. Washington, Year Book*, No. 32, p. 268.

Delle Chiaje, S.

1841 Descrizione e notomia degli animali invertebrati della Sicilia citeriore . . . Vol. 4, 142 pp., Atlas (to Vols. 1-8), 181 pls., Naples.

Eschscholtz, Fr.

1829 System der Acalephen . . . 6+190 pp., 16 pls., Berlin.

Fewkes, J. W.

1882 On the Acalephae of the East Coast of New England. *Bull. Mus. Comp. Zool.*, Vol. 9, pp. 291-310, 1 pl.

1883 On a few Medusae from the Bermudas. *Bull. Mus. Comp. Zool.*, Vol. 11, pp. 79-90, 1 pl.

1886 Report on the Medusae collected by the U. S. F. C. Steamer Albatross, in the region of the Gulf Stream, in 1883-'84. *Rept. U. S. Fish. Comm.* for 1884, pp. 927-977, 10 pls.

1889 Report on the Medusae collected by the U. S. Fish Commission Steamer Albatross in the region of the Gulf Stream, in 1885-'86. *Rept. U. S. Commissioner of Fish and Fisheries* for 1886, pp. 513-534, 1 pl.

Foerster, R. E.

1923 The Hydromedusae of the West Coast of North America, with Special Reference to the Vancouver Island Region. *Contr. Canadian Biol.*, N. S., Vol. 1, No. 12, pp. 219-277, 5 pls.

Forskål, Petrus.

1775 Descriptiones animalium . . . quae in itinere Orientali observavit . . . Post mortem auctoris edidit Carsten Niebuhr. 19+1+34+164 pp. Hauniae.

Gegenbaur, C.

1856 Versuch eines Systemes der Medusen . . . *Zeit Wiss. Zool.*, Vol. 8, pp. 202-273, Pls. 7-10.

Haacke, Wilhelm.

1886 Über die Ontogenie der Cubomedusen. *Zool. Anz.*, Vol. 9, pp. 554-555.

1887 Die Scyphomedusen des St. Vincent Golfes. *Jena Zeitschr. Naturwiss.* Vol. 20, pp. 588-638, Pls. 35-37.

Haeckel, Ernst.

1877 Prodrom. System. Medus. (Cited from Haeckel, 1880).

1879 Das System der Medusen. Theil 1. System der Craspedoten. *Jena Denkschr. Med.-Naturwiss. Gesell.*, Vol. 1, 25+360 pp., Atlas of 40 pls.

1880 System der Acraspeden. Zweite hälfte des Systems der Medusen. *Jena Denkschr. med.-naturwiss. Gesell.*, Vol. 1, Pt. 2, pp. 361-672.

1881 Report on the deep sea Medusae . . . *Rept. Sci. Res. H. M. S. Challenger. Zool.* Vol. 4, 105+154 pp., 32 pls.

Hargitt, C. W.

1905 Notes on the Variations in Rhegmatodes. *Biol. Bull.*, Vol. 9, pp. 368-377.

Hartlaub, C.

1907 Craspedote Medusen. 1 Teil, 1 Leif.: Familie I, II. Codoniden und Cladonemiden *Nordisches Plankton*, Zool., Vol. 6, *Coelenterata*, pp. 1-135, 126 text-figs.

1914 Craspedote Medusen. 1 Teil, 3 Leif.: Familie IV. Tiaridae. *Nordisches Plankton, Zool.*, Vol. 6 *Coelenterata*, pp. 237-364.

Jespersen, P.

1915 Sternoptychidae (Argryopelecus and Sternoptyx). *Rep. Danish Ocean. Exp.* 1908-1910 *to the Mediterranean and Adjacent Seas*, No. 3, Vol. 2, (*Biology*), A. 2, pp. 1-33, 6 text-figs.

Kölliker, Albert.

1853 Über Scheibenquallen. *Zeit. Wiss. Zool.*, Vol. 4, pp. 320-329.

Kramp, P. L.

1913 Medusae collected by the "Tjalfe" Expedition. *Vidensk. Meddl. Dansk naturh, foren. Kjóbenhavn*, Vol. 65, pp. 257-286, 4 text-figs.

1914 Meduser og Siphonophorer *Medd. om Grönland*, Pt. 23, pp. 381-456.

1919 Medusae. Part 1. Leptomedusae. *Danish Ingolf-Exped.*, Vol. 5, No. 8, 111 pp., 5 pls.

1920 List of Medusae collected by the M. S. "Armauer Hansen" in the North Atlantic in 1913. *Bergens Mus. Aarbog*, 1917-1918, No. 8, 7 pp.

1920a Anthomedusae and Leptomedusae. *Rept. Sci. Res. "Michael Sars" North Atlantic Deep Sea Exped.*, Vol. 3, Pt. 2, 13 pp., 1 pl., 6 text-figs.

1924 Medusae. *Rep. Dan. Ocean. Exp.* 1908-1910 *to the Mediterranean and Adjacent Seas*, No. 8, Vol. 2, *Biol.* H. 1, 67 pp., 40 text-figs., 12 charts.

1926 Medusae. II. Anthomedusae. *Danish Ingolf-Exped.*, Vol. 5, Pt. 10, 102 pp., 2 pls.

1928 Papers from Dr. Th. Mortensen's Pacific Exped. 1914-1916. XLIII. Hydromedusae. I. Anthomedusae. *Vidensk. Meddl. Dansk Naturhist. Foren. i Kjóbenhavn*, Vol. 85, pp. 27-64.

1933 Craspedote Medusen. Teil III. Leptomedusen. *Nordisches Plankton. Zool.*, Vol. 6: *Coelenterata*, pp. 541-602, Figs. 1-68.

KRAMP, P. L. and DAMAS, D.
1925 Les Méduses de la Norvège. Introduction et Partie spéciale I. *Vidensk. Meddl. Dansk Naturhist. Foren. i Kjóbenhavn,* Vol. 80, pp. 217-323, Pl. 35.

KRUMBACH, T.
1925 Scyphozoa, in Kükenthal und Krumbach, Handbuch der Zool., Vol. 1, Pt. 4, pp. 522-608.

LEAVITT, B. B.
1935 A Quantitative Study of the Vertical Distribution of the Larger Zoöplankton in Deep Water. *Biol. Bull.,* Vol. 68, pp. 115-130.

LELOUP, E.
1935 *Halammohydra* et les Siphonophores Chondrophorides. *Bull. Mus. roy. hist. nat. Belg.,* Vol. 11, No. 23, 4 pp.

LELOUP, E., and HENTSCHEL, E.
1935 Die Verbreitung der Calycophoren Siphonophoren im Südatlantischen ozean. *Wiss. Ergeb. Deutschen Atlantischen Exped. auf dem . . . "Meteor,"* 1925-1927, Vol. 12, Pt. 2, pp. 1-31.

LESSON, R. P.
1830 Voyage autour du monde sur la Corvette de sa majesté, La Coquille . . . 1822, 1823, 1824, et 1825 . . . Zool., Vol. 2, Pt. 2, Div. 2, Zoophytes, 35 pp. and Atlas, Zoophytes, 16 pls.
1843 Histoire naturelle des Zoophytes. Acalèphes. Paris, 8+596 pp. Atlas of 12 pls.

LIGHT, S. F.
1914 Some Philippine Scyphomedusae . . . *Philippine Jour. Sci.,* Vol. 9, Sect. D, pp. 195-231.
1921 Further notes on Philippine Scyphyomedusan Jellyfishes. *Philippine Jour. Sci.,* Vol. 18, pp. 25-47.

LINNÉ, CARL VON
1758 Systema Naturae . . . Ed. 10, Vol. 1, 823 pp. Holmiae.

MAAS, OTTO.
1893 Die craspedoten Medusen. *Ergebn. Plankton Exped. . . .* Vol. 2, K. c., 107 pp., 6 pls., 2 charts.
1897 Reports on an Exploration off the West Coasts of Mexico, etc. XXI. Die Medusen. *Mem. Mus. Comp. Zool.,* Vol. 23, 92 pp., 15 pls.
1904 Méduses provenant des campagnes des Yachts *Hirondelle et Princesse Alice* (1886-1903). *Res. camp. sci. . . . par Albert* 1er, *Prince souverain de Monaco.* Vol. 28, 71 pp., 6 pls.
1905 Die craspedoten Medusen der Siboga Expedition. *Siboga Exped. Monogr.* 10, 84 pp., 14 pls.
1906 Medusen. *Rés. Voyage S. Y. Belgica en* 1897-1898-1899 . . ., *Zoologie,* pp. 1-30, 3 pls.

MAYER, A. G.
1894 Cruise of the Steam Yacht "Wild Duck" in the Bahamas . . . III. An Account of some Medusae obtained in the Bahamas. *Bull. Mus. Comp. Zool.,* Vol. 25, pp. 235-242, 3 pls.
1900 Some Medusae from the Tortugas, Florida. *Bull. Mus. Comp. Zool.,* Vol. 37, pp. 11-82, 44 pls.
1904 Medusae of the Bahamas. *Mem. Nat. Sci., Brooklyn Inst. Arts and Sci.,* Vol. 1, 33 pp., 7 pls.
1906 Medusae of the Hawaiian Islands collected by the Steamer Albatross in 1902. *Bull. U. S. Fish Comm.,* Vol. 23, Pt. 3, pp. 1131-1143, 3 pls.
1910 Medusae of the world. 3 vols. *Carnegie Inst., Washington, Publ.* No. 109.
1915 Medusae of the Philippines and of Torres Straits. *Papers from Dept. Mar. Biol.,* Vol. 8, Publ. 212, *Carnegie Inst., Washington,* pp. 157-202, 3 pls., 7 text-figs.
1917 Report upon the Scyphomedusae collected by the U. S. Bureau of Fisheries Steamer "Albatross" in the Philippine Islands and Malay Archipelago. *Bull. U. S. Nat. Mus.,* 100, Vol. 1, Pt. 3, pp. 175-233.

MENON, M. G. K.
1930 The Scyphomedusae of Madras and the neighboring coast. *Bull. Madras Govt. Mus., N. S. Nat. Hist. sect.*, Vol. 3, No. 1, 28 pp. 3 pls.

MÜLLER, F.
1858 Zwei neue Quallen von Santa Catharina (Brasilien). *Abhandl. natf. Ges. Halle*, Vol. 5, pp. 1-12, 3 pls.
1861 Polypen und Quallen von Santa Catharina. *Olindias sambaquiensis* n. sp. *Archiv. für Naturges.* Jahrg. 27, pp. 312-319, Fig. 9.

NEPPI, V. and STIASNY, G.
1913 Die Hydromedusen des Golfes von Trieste. *Arb. Zool. Inst. Wien*, Vol. 20, pp. 1-70 or (23)-(92), 4 pls.

PÉRON, F. and LESUEUR, C. A.
1809 Histoire générale et particulière de tous les animaux qui composent la famille des Méduses. *Ann. Mus. Hist. Nat. Paris*, Vol. 14, pp. 218-228.

QUOY, J. R. C. and GAIMARD, J. P.
1827 Observations Zoologiques faites à bord de l'*Astrolabe* en mai 1826 dans le détroit de Gibraltar. *Ann. Sci. Nat.*, Vol. 10, pp. 172-193, Pls. 4-6.

RANSON, G.
1936 Méduses provenant des Campagnes du Prince Albert 1er de Monaco. *Res. camp. sci. Monaco . . .* Vol. 92, 245 pp., 2 pls.

RAO, H. S.
1931 Notes on Scyphomedusae in the Indian Museum. *Rec. Indian Mus. Calcutta*, Vol. 33, Pt. 1, pp. 25-62, pls. 3-4.

REMANE, A.
1927 Halammohydra, ein eigenartiges Hydrozoon der Nord- und Ostsee. *Zeit. f. Wiss. Biol.*, Abt. A, *Zeit f. Morphol. u. Ükol. der Tiere*, Vol. 7, pp. 643-677, 21 text-figs.

REYNAUD, M.
1830 In Lesson, R. P. Centurie zoologique . . . Paris 10, 244 pp., 80 pls.

SEMPER, CARL.
1863 Riesebericht. *Zeit. f. Wiss. Zool.*, Vol. 13, pp. 558-570, Pls. 38-39.

STIASNY, G.
1914 Zwei neue Pelagien aus der Adria. *Zool. Anz.*, Vol. 44, pp. 529-533.
1919 Die Scyphomedusen-Sammlung des naturhistorischen Reichsmuseums in Leiden. I. Die Carybdeiden (Cubomedusen). *Zool. Mededeel. Rijks. Mus. Nat. Hist. Leiden*, Vol. 5, pp. 33-58, 14 text-figs.
1919a Die Scyphomedusen-Sammlung der Naturhistorischen Reichsmuseums in Leiden. II. Stauromedusae, Coronatae, Semaeostomeae. *Zool. Mededeel., Rijks. Mus. Nat. Hist., Leiden*, Vol. 5, pp. 66-99, 3 text-figs.
1922 Papers from Dr. Th. Mortensen's Pacific Expedition 1914-1916. XIII. Die Scyphomedusen-Sammlung von Dr. Th. Mortensen . . . *Vidensk. Meddel Dansk Naturh. Foren., Kjóbenhavn*, Vol. 73, pp. 513-558.
1924 Ueber einige von Dr. C. J. Van der Horst bei Curaçao gesammelte Medusen. *Bijdagen tot der Dierkunde. Amsterdam*, Vol. 23, pp. 83-91.
1926 Ueber einige Scyphomedusen von Puerto Galera, Mindoro (Philippinen). *Zool. Mededeel., Rijks Mus. Nat. Hist., Leiden*, Vol. 9, pp. 239-248.
1929 Ueber einige Scyphomedusen aus dem Zoologischen Museum in Amsterdam. *Zool. Mededeel., Rijks Mus. Nat. Hist., Leiden*, Vol. 12, pp. 195-216.
1930 Scyphomedusen. Rés. sci. Voyage aux Indes Orientales Néerlandaises . . . *Mem. Mus. Roy. Hist. Nat. de Belgique.* Hors série, Vol. 2, Pt. 4, 11 pp.
1931 Ueber einige Coelenterata von Australien. *Zool. Meded., Rijks Mus. Nat. Hist., Leiden*, Vol. 14, pp. 27-40.
1934 Scyphomedusae. *Discovery Repts.*, Vol. 8, pp. 329-396, Pls. 14-15.
1935 Die Scyphomedusen der Snellius expedition. Verh. konink. acad. Wet. Amsterdam afd. natuurk., 2nd Section, Vol. 34, No. 6, pp. 1-44, 9 text-figs., 1 pl.

1937 Scyphomedusae. Sci. Rep. John Murray Exped., 1933-34, Brit. Mus. (N. H.), Vol. 4, No. 7, pp. 203-242, 1 pl., 14 text-figs., 2 maps.

SCHWARTZ, C.

1788 *Neue Abhandl. Schwed Acad. Deutsche liebers.*, 1789, p. 195, Pl. 6, Fig. 1, (not accessible).

THIEL, M. E.

1928 Die Scyphomedusen des Zoologischen Staatsinstituts und Zoologischen Museums in Hamburg. 1. Cubomedusae, Stauromedusae und Coronatae. *Mitt. Zool. Staats. Inst. und. Zool. Mus. Hamburg*, Vol. 43, pp. 1-34.

1931 Beiträge zur Planktonbevölkerung der Weddellsee nach den Ergebnissen der Deutschen Antarktischen Expedition, 1911-1912. *Internat. Rev. Hydrobriol u. Hydrograph.*, Vol. 25, pp. 305-332, 1 text-fig.

1932 Die Hydromedusenfauna des Nördlichen Eismeeres . . . *Arch. f. Naturgesch.*, n. s., Vol. 1, pp. 435-514.

1932a Übersicht über die Hydromedusen der Arktis. *Fauna Arctica*, Vol. 6, pp. 121-158.

1935 Die Besiedlung des Südatlantischen Ozeans mit Hydromedusen. *Wiss. Ergeb. Deutschen Atlantischen Exped. auf dem . . . "Meteor"*, 1925-1927, Vol. 12, Pt. 2, pp. 32-100.

1936 Systematische Studien zu den Trachylinae der Meteorexpedition. *Zool. Jahrb.* Abt. Syst. Vol. 69, pp. 1-92.

TOTTON, A. K.

1936 Plankton of the Bermuda Oceanographic Expeditions. VII. Siphonophora taken during the year 1931. *Zoologica.* New York Zool. Soc., Vol. 21, Pt. 4, pp. 231-240.

UCHIDA, TOHRU.

1927 Studies on Japanese Hydromedusae. 1. Anthomedusae. *Jour. Fac. Sci. Imp. Univ., Tokyo*, Sect. 4, Zool., Vol. 1, Pt. 3, pp. 145-241, Pls. 10-11.

1928 Studies on Japanese Hydromedusae. 2. Trachomedusae and Narcomedusae. *Japanese Jour. Zool.*, Vol. 2, pp. 73-97.

1929 Studies on the Stauromedusae and Cubomedusae, with Special Reference to their Metamorphosis. *Japanese Jour. Zool.*, Vol. 2, pp. 103-193, Pls. 3-5.

1934 A Saemostome Medusa with Some Characters of Rhizostomae. *Proc. Imp. Acad., Tokyo*, Vol. 10, No. 10, pp. 698-700.

VANHÖFFEN, ERNST.

1902 Die acraspeden Medusen der deutschen Tiefsee-Expedition 1898-1899. *Wiss. Ergeb. deutschen Tiefsee- Exped. auf dem Dampfer "Valdivia"*, 1898-1899, Vol. 3, pp. 1-52, Pls. 1-8.

1902a Die craspedoten Medusen der deutschen Tiefsee-Expedition 1898-1899. 1. Trachymedusen. *Wiss. Ergeb. deutschen Tiefsee-Exped. auf dem Dampfer "Valdivia"*, 1898-1899, Vol. 3, pp. 53-86, Pls. 9-12.

1908 Die Lucernariden und Scyphomedusen. *Deutsche Südpolar Exped.* 1901-1903 . . . Vol. 10, *Zool.* Vol. 2, pp. 25-49, 11 text-figs.

1908a Die Narcomedusen. *Wiss. Ergeb. Deutschen Tiefsee-Exped. auf dem Dampfer "Valdivia"*, 1898-1899, Vol. 19, Pt. 2, pp. 43-74, Pls. 7-9, 5 text-figs.

1911 Die Anthomedusen und Leptomedusen der Deutschen Tiefsee-Exped. 1898-1899. *Wiss. Ergeb. Deutschen Tiefsee-Exped. auf dem Dampfer "Valdivia"*, 1898-1899, Vol. 19, Pt. 5, pp. 193-233, Pl. 22, 21 text-figs.

1912 Die Craspedoten Medusen der Deutschen Südpolar-Expedition. *Deutsche Südpolar-Expedition* 1901-1903. Vol. 13, *Zool.* Vol. 5, pp. 351-396, Pl. 24-25, 25 text-figs.

1912a Die craspedoten Medusen des "Vettor Pisani." *Zoologica*, Stuttgart, Vol. 26, Pt. 67, pp. 1-34, 2 pls., 6 text-figs.

1913 Über westindische Medusen. *Zool. Jahrb. Supp.* Vol. 11, pp. 413-432.

VON LENDENFELD, R.

1884 The Scyphomedusae of the Southern Hemisphere. Pt. 2, *Proc. Linn. Soc., New South Wales*, Vol. 9, pp. 242-249.

APPENDIX[1]

Net Number	Zancleopsis dichotoma	Bougainvillia niobe	Pandea conica	Pandea rubra	Heterotiara anonyma	Calycopsis sp?	Chromatonema rubrum	Aequorea floridana	Olindias phosphorica tenuis	Rhopalonema velatum	Pantachogon haeckeli	Colobonema typicum	? Crossota brunnea	? Crossota	Trachynemidae genus?	Halicreas minimum	Halicreas glabrum	Halitrephes valdiviae	Liriope tetraphylla	Geryonia proboscidalis	Cunina sp?	? Solmissus incisa	Aegina citrea	Aeginura grimaldii	? Aeginura grimaldii	? Pegantha clara	Carybdea marsupialis xaymacana	Carybdea alata	Tamoya haplonema	Periphylla hyacinthina	Nausithoe punctata	Atolla wyvillei	Linuche unguiculata	Pelagia noctiluca	? Poralia rufescens	Aurellia aurita	Unidentifiable
13																														1							
16																														3							1
17																														2							
18																								1													
21																																					2
22																								1													1
23																														1		2					
24																								1													2
25																1	2																				
26												2				1									1					5		2					
29																																1					
31																																					2
32										5																											
33																														2							
34																														3							
35										1																											2
36											2													1								1					
39										2		1																		1		3					
41														1		1								2								1					2
42											1														1												1
43										4						1	1													1							1
44										1						3														1							1
45																														1							
48																								2													
49																								2													1
50																										1									1		1
51																			1																		1
52											4													1													
53																								2						1		2					2
56																1	1																				
58																																					1
60																1																					
62																1	1															1					2
64											1													3													1
65																2									1												
66														2		1								3								4					
67										1						1								2													
68																2	2																				
69										2						1								1													
73																								1													
74														1																		2					
75														1		1	1																				
76																2									3												
78																								4								1					

79					1																																2
81																1																					1
83																1	1													1							
88																														2							
89																	1													1							
94												2																									
95												1																									1
97										1																											1
98										1																											
99												2																									
100										1																				7		2					
101														1																							
102										3																						2					
103																														2							
104																																					1
105												1																				1					
106																	2																				1
108																1																					
110															3	1									2												1
111																								2								2					
114														1			1													1							
115																1																					
116																														3							
118																														1		1					
119																																					
121																								1						1							
122																								2								1					
124																2																					
135																		1												2							
137														1										1													
138														1		1																					
141																														7							
142																														1		1					
143																									1												2
144																2	4													1							1
145															3		3													2							1
153																																					1
154																		1												4		2					
157																7	4									1				1							
178																														1							
196																														2		1					
199																																					1
203																1																					
218																	1																				
220														1																							
221																														1		2					
234											1																			2							1
235																														1							1
240												1																		2		1					
241													2			1														1							
242																	1				1																
247																3	1	1														1			1		1
253																																1					
261																														1							
262																																					1

---

[1] This table does not include a number (less than 10) of specimens for which no Net Number was available at the time of compiling table.

Net Number	Zanclepsis dichotoma	Bougainvillia niobe	Pandea conica	Pandea rubra	Heterotiara anonyma	Calycopsis sp?	Chromatonema rubrum	Aequorea floridana	Olindias phosphorica tenuis	Rhopalonema velatum	Pantachogon haeckeli	Colobonema typicum	? Crossota brunnea	? Crossota	Trachynemidae genus?	Halicreas minimum	Halicreas glabrum	Halitrephes valdiviae	Liriope tetraphylla	Geryonia proboscidalis	Cunina sp?	? Solmissus incisa	Aegina citrea	Aeginura grimaldii	? Aeginura grimaldii	? Pegantha clara	Carybdea marsupialis xaymacana	Carybdea alata	Tamoya haplonema	Periphylla hyacinthina	Nausithoe punctata	Atolla wyvillei	Linuche unguiculata	Pelagia noctiluca	? Poralia rufescens	Aurelia aurita	Unidentifiable
263																							2														
267																														4							1
268																																					1
269															1	2	1													1							
270																4	5							1						1							
271																17	6									1											
273																														2							
274																														1							
279																														2							
280																														1							
291																														14							1
292												3											1							7		3					
293												3				6								1						6		1	1				
294																							1														
295												1		1	2	3	2							1	2					9		2					
296											4	1											1							4		1				1	
297																2	3																				
343																																					1
357																1		1																			
359																	1																				1
360																1									1												1
362										1														2													1
368							1																									1					
371																																					1
383																1																					
400												1												1													
401																1																					
405																3														1							
406																1																					
427																								1													
434												2																		11		6					
442																2								3													
447																									1												
448																												1									
449															1		1													1							
451																		1																			
455																								1													2
459																												1									
466																2	1																				
468																3								3													
481																3								1													
484																																					1
488																1	1						2		1												1
501																1	2																				

506																	1																				
539											2						1							2								2					
543																														1							
544																																1					
545																														1		1					
546																														1		1					
547																														1							
548																														1							
551																														1							1
552											5																			1		1					
553																																1					2
554											2																										
555																														1							
556											1																					1					
561																																1					
562		1		1														1						1						1		3					3
563																																1					1
564																							1														
565												1																				10					
566																1							1														
568																																1					
569																2																					
570																1																					
574															1																	2					
575											1																					1					
576																1							1														
577															1															1							
579																																					1
580																		1																			
581										1																				1							
582											1													1								1					
588																																1					
590																1														2							
595																														1							
596																																2					
597												1																				1					
598											3				4										1							2					
599																1						1										1					
601																																1					1
605												1												5								1					
606												1												1								1					
607				1								1																									
609																																					1
610												1																									
611																																1					
612																								3													
613				1											1					1																	
614																		1																			
618																														1		2					
619																														1		2					1
620										1														1						1							
621																				1				5						1							1
624																														1							
625												1																		2		1					
626												1																		2		7					1

Net Number	Zancleopsis dichotoma	Bougainvillia niobe	Pandea conica	Pandea rubra	Heterotiara anonyma	Calycopsis sp?	Chromatonema rubrum	Aequorea floridana	Olindias phosphorica tenuis	Rhopalonema velatum	Pantachogon haeckeli	Colobonema typicum	? Crossota brunnea	? Crossota	Trachynemidae genus?	Haliceras minimum	Haliceras glabrum	Halitrephes valdiviae	Liriope tetraphylla	Geryonia proboscidalis	Cunina sp?	? Solmissus incisa	Aegina citrea	Aeginura grimaldii	? Aeginura grimaldii	? Pegantha clara	Carybdea marsupialis xaymacana	Carybdea alata	Tamoya haplonema	Periphylla hyacinthina	Nausithoe punctata	Atolla wyvillei	Linuche unguiculata	Pelagia noctiluca	? Poralia rufescens	Aurellia aurita	Unidentifiable
627																							1	3							1						1
628											1											1		4													
631																								1						1		2					
632										1												1		3								3					
633																																1					
634										2																											
635																		1						1													
637												1																				4					
638																								1						1							
639																								2								2					1
640										2				1		1																					
641												1																									
642													2																								
643																																					
644														1	4															1							
645																								2						3							
646																								2						1							
647														1																		4					3
648											1					1																2					
649			1																				1														
652																								3								1					
653												1																									
654																1								2						1							
657											2												1									1					
658											1																										
659											2																					1					
663																												1									
665													1											6													1
666											2			3									1									1					
674																														1		1					1
676																																1					
680												1			1							1		6													
681																								3								1					1
682										1						3																1					
683																1																					
684											1					1																					
685											2													2								1					
686																							1							1							
687																																1					
688																														1		2					
690																																	2				2
691											1																					1					1
692																							1							2							
693																							1														

694																																	1				1
695											2																										
698											3													3								1					
699																														1							1
700																						1		4													
701																3																1					
702																								1													
703																1																					
707																														2		8					
708																							1	2													1
709											1							1												1							
710																	2													2							
712																								1						1							1
713																						1															1
714																		1																			
715															1									2													
716																									1					1							
717											1					1																					
718											1				2	1																					
719																								4							2	1					
720										1														3		1						2					1
721											1													2						1		1					
722																1														1							
723																4														1							1
724														1		1								1						1							
725																																					
726															1									1						1					1		
727																1																2					
728																1														1							
730										1						2														1							
731																														1							
732												1												1						3							1
733													1																								2
734																														1							
735																						1															
736											1					1														2							
738		1													1																						
739											1																					1					
740																								1													
741																1																1					
742											1						1							1													2
745																		1					1	3			4					1					
746																1								1						1							1
748											1			1																		1					
750																1														1							
751																1																					
752																														1							
753																						1		1													1
756																1														3							
757											1																										
758																														3							
759																								3						1							
760												2												4													
761																								1													1
762																							1							3							

Net Number	Zancleopsis dichotoma	Bougainvillia niobe	Pandea conica	Pandea rubra	Heterotiara anonyma	Calycopsis sp?	Chromatonema rubrum	Aequorea floridana	Olindias phosphorica tenuis	Rhopalonema velatum	Pantachogon haeckeli	Colobonema typicum	? Crossota brunnea	? Crossota	Trachynemidae genus?	Halicreas minimum	Halicreas glabrum	Halitrephes valdiviae	Liriope tetraphylla	Geryonia proboscidalis	Cunina sp?	? Solmissus incisa	Aegina citrea	Aeginura grimaldii	? Aeginura grimaldii	? Pegantha clara	Carybdea marsupialis xaymacana	Carybdea alata	Tamoya haplonema	Periphylla hyacinthina	Nausithoe punctata	Atolla wyvillei	Linuche unguiculata	Pelagia noctiluca	? Poralia rufescens	Aurellia aurita	Unidentifiable
765																1						1															
766																														2							
767															2	1		2												1		9					
770														1																		2					
771																																					1
772																														2							
773																														2	1						
774																4														1		2					
775																														2							
777												2																				2					
778																		1						3						1		2					
779														2									2	2													
780											1																			1							
781																1								1								1					
785															2															3							1
787													2			1																5					
788																1																					1
789											1																					1					
791																														1							
793										1														4							1						1
794													1											1													1
795															1	1														1							
796																														3							
797																														1							
798																														2		2					
799															2	1						1								1		4					
800				1																			2									1					1
801																														1		1					2
804																								1						5		1					
805											1	2												1													
806																																1					
807														1	2																						
808																																2					2
809											1												1							3							
810																								3								2					
811																								1													
812		1												2										3		1						1					1
813												1																									
814																																					2
815														1		1																					
816																																					
818																		1												2							
822																														3							
824															1																	2					

825																													1							2
826																															2					
827															1														1							
829																															1					
830																		1																		
831																															4					
832																													1							
835																													1							
836																													4							1
837																													2							
838																													2		2					
840								2	3																		1									
842																								1						1							2
843																		1																		1
844														1																						
845																																				1
846																													5		2					
848																						1								4							
849														2										6												
850																				1										1		1					
851																													2							1
852																2								1						4							
853												1																								
854											1		1																	2							
855																													1							
856																																				1
857																3							1													
858																1														2							
860																													2		1					2
861																								2								2					2
862		1									2																									
863																5																1		1			1
864											3					2																				
865																															2					
866											1																									
867												1		1	3																					
868																																				1
869													1			1																				
874												1											1													1
875																1																1					
880																														2						1	
881											1																					1					
882															2								1			1				1		1					
883																														2							
885														1	1							1	2	1						1		2					
886																														2							
887																1																				1
890																	2																			
891														1								1														
892																															1					
893																2																				
894																								2												
895																														1							
896															2															1							
897											3																									

Net Number	Zancleopsis dichotoma	Bougainvillia niobe	Pandea conica	Pandea rubra	Heterotiara anonyma	Calycopsis sp?	Chromatonema rubrum	Aequorea floridana	Olindias phosphorica tenuis	Rhopalonema velatum	Pantachogon haeckeli	Colobonema typicum	? Crossota brunnea	? Crossota	Trachynemidae genus?	Halicreas minimum	Halicreas glabrum	Halitrephes valdiviae	Liriope tetraphylla	Geryonia proboscidalis	Cunina sp?	? Solmissus incisa	Aegina citrea	Aeginura grimaldii	? Aeginura grimaldii	? Pegantha clara	Carybdea marsupialis xaymacana	Carybdea alata	Tamoya haplonema	Periphylla hyacinthina	Nausithoe punctata	Atolla wyvillei	Linuche unguiculata	Pelagia noctiluca	? Poralia rufescens	Aurelia aurita	Unidentifiable
898																1														1							1
899																																					
902																										1											
903																																					1
905																														3							
915		1								2																											3
916										2	1																			1							
917														1																1		1					
918																														2							
919																1																					
921																														2							
922	1																																				
925																														1							
926															3																	2					
928																														1		1					
929											1														1												
930																														1							
931																1																					
932																2														1							
933																2														1							
935		1												1		1											1			1							
937												1																		2		1					
938																																1					
939												1																		2							1
940																3														1							
942																1	5																				
943																																1					
945										1																											1
947																1																					2
949																									2												2
951																														2							1
954																																					1
959						2	1			1				1										3		1											1
962																	3																				
963																1														1							
964											3	1																				1					
967										1				1				1													1						
968															1																						
969																3																					
970														1		6														1							
971																							1														
977					1																						14										
978																											18										
979																											66	1									

Surface June 25, 1929																													1							
Surface July 11, 1929		1																																		
Surface July 23, 1929																																	1			
Surface Sept. 8, 1930																																		1		
Surface Oct. 16, 1930																											1									10
Surface June 8, 1929																																	many			

Contribution No. 152

THE SINKING OF DECOMPOSING PLANKTON IN SEA WATER AND ITS RELATIONSHIP TO OXYGEN CONSUMPTION AND PHOSPHORUS LIBERATION

H. R. SEIWELL AND GLADYS EDDY SEIWELL[1]

Abstract

The present investigation represents an attempt to obtain certain fundamental theoretical data on physical and chemical processes accompanying decomposition of marine organic matter which are needed, in particular, for investigation of the origin of the minimum oxygen concentration in the ocean basins. Five separate experiments (in duplicate), ranging up to 363 hours duration, were carried out under controlled laboratory conditions. For each experiment weighed amounts of fresh zoöplankton from Woods Hole vicinity were permitted to decompose in a light-proof apparatus; and rates of oxygen consumption, phosphorus liberation, and settling velocities of the organic debris estimated at stated intervals.

The analytical results indicate a divergence of the two chemical processes in so far as laboratory conditions are concerned. The rate of oxygen consumption from 0 to 280 hours after death decreased approximately linearly with time. On the other hand, phosphorus liberation showed no apparent continuous regularity, but there was a rapid liberation of phosphate for approximately 24 hours after death of the organisms with a rapid decline thereafter. Settling velocities of the decomposing organic debris in sea water (density, σ_t : 20.66–21.70) decreased from about 0.37 to 0.03 cm/sec between 2 and 363 hours after death of the organisms. These data are subjected to special treatment on the assumption of the applicability of Stokes' Law (for motion of a sphere through a viscous medium), and the mean value of the density and variation of the "equivalent radius" estimated. The "equivalent radius" of the organic particles appears to decrease linearly with time.

Results of the analysis of settling velocities were applied to an oceanic area (represented by "Atlantis" station 1170) not with the intention of illustrating actual conditions in nature, but rather to show how results of controlled laboratory experiments may be combined with a natural oceanographic set up to obtain basic information on laws regulating decomposition in the sea. Calculations were made, on the basis of derived equations, to illustrate relationship between the reduction of "equivalent radii" with depth and the relationship between time and depth for organic particles (of various initial sizes) as they sink through water of known density stratification. It appears reasonable to assume that the results indicate, in a general way, the mechanism underlying certain of the biological activities which alter the distribution of non-conservative properties (such as oxygen) in the sea.

---

[1] Contribution No. 152 from the Woods Hole Oceanographic Institution.

PROCEEDINGS OF THE AMERICAN PHILOSOPHICAL SOCIETY,
VOL. 78, NO. 3, JANUARY, 1938
Reprint *Printed in U. S. A.*

I. Introduction

This paper is a report on a series of laboratory experiments carried out for the purpose of obtaining elementary data on the relation between the sinking of decomposing marine zooplankton in sea water and its consumption of oxygen and liberation of phosphorus. The experiments, carried out under controlled laboratory conditions, were planned as an approach to the quantitative measurement of decomposition activity in the sea, and, while the artificial conditions of the laboratory disturb the equilibria of the natural reactions and limit the practicability of the application of the final results to the sea, an even greater hindrance in investigations of this kind is in the selection of the kind of material for study.

The interpretation of organic decomposition studies is difficult particularly in view of the limited knowledge of the fundamental structure on which all problems of marine organic decomposition rest, namely, the relative significance of its various size classes in nature. Hence, until this and similar questions of practical oceanography are investigated the application of results of physical and chemical laboratory experiments can do little but suggest, in a general way, the laws underlying the biochemical and physiological mechanisms of the sea.

It is the plan of this paper to present first the results of the laboratory experiments and then to apply these data to a specified part of the North Atlantic ocean. No claim is made that this oceanic application gives a correct picture of what happens in nature, but rather indicates how a type of organic matter might behave in the water if it should act in nature as in the laboratory.

II. Methods

The animal plankton (chiefly copepod) used for analyses was collected with a one meter diameter stramin net at depths of 10 to 30 meters in the vicinity of Woods Hole. Weighed amounts of wet plankton were placed in amber glass bottles in a light proof apparatus where a continuous flow of sea water was maintained over the decomposing material. Samples both of water and plankton were removed at various intervals (up to 280 hours after death) for estimation of oxygen consumption and phosphorus liberation on the former, and of free fall velocities on the latter. An approximately constant oxygen pressure was maintained in the bottles at temperatures between 22° and 25° throughout the experiment.

Oxygen and phosphate were estimated by standard methods of oceanographic procedure (Seiwell, 1934 and 1935), and, for estimation of the free fall velocities, small quantities of the decomposing organic matter were allowed to settle in a Nessler tube through a measured distance (25 centimeters) of sea water of known density.

III. Experimental Results

(a) *Oxygen Consumption*

Amounts of plankton ranging from 0.4 to 2.4 grams (wet weight) were used for each of the experiments. The results, expressed as grams of oxygen consumed $\left(-\frac{dO_2}{dt}\right)$ per hour per gram of wet plankton, which are plotted in Fig. 1 against age of the dead plankton (referring from the time the plankton was put in the apparatus at the beginning of each experiment) suggest a linear reduction with time in the consumption rate. The best straight line fitting these data (for 0 to 280 hours), by the method of least squares, has the equation:

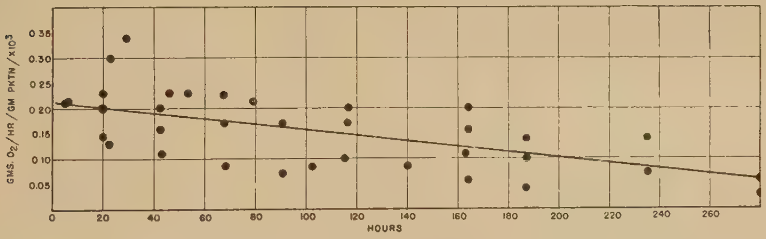


Fig. 1. Time variation of oxygen consumption based on data from five controlled laboratory experiments. The straight line trend has been fitted by the method of least squares.

$$-\frac{dO_2}{dt} = 10^{-3}\left[0.2154 - 0.000551\,t\right] \tag{1}$$

TABLE 1

Experiment No. 1		Experiment No. 2		Experiment No. 3		Experiment No. 4	
Age dead plankton	g. P per g. per hour	Age dead plankton	g. P per g. per hour	Age dead plankton	g. P per g. per hour	Age dead plankton	g. P per g. per hour
$20^h\ 00'$	$10,000\times10^{-9}$	$21^h\ 00'$	$3,660\times10^{-9}$	$23^h\ 00'$	$8,940\times10^{-9}$	$22^h\ 45'$	$4,320\times10^{-9}$
$46^h\ 00'$	900×10^{-9}	$117^h\ 30'$	negative	$42^h\ 15'$	0	$42^h\ 45'$	negative
$117^h\ 00'$	negative	$141^h\ 45'$	negative	$68^h\ 30'$	negative	$67^h\ 15'$	0
$140^h\ 30'$	360×10^{-9}	$164^h\ 00'$	negative	$90^h\ 30'$	negative	$90^h\ 30'$	negative
$164^h\ 30'$	0	$188^h\ 15'$	60×19^{-9}	$163^h\ 00'$	negative	$164^h\ 00'$	negative
$188^h\ 00'$	0	$284^h\ 15'$	0				
$284^h\ 00'$	0						

where t (hours) is the age of the dead plankton, and, $-\frac{dO_2}{dt}$, the oxygen consumption expressed as grams of oxygen per hour per gram of (wet) plankton at temperatures of 22° to 25°. In these experiments fresh sea water continually flowed over the decomposing material and the results would appear to be but little influenced by the decomposition of other suspended or dissolved organic material present in the sea water itself such as, for instance, has been reported by Waksman and Renn (1936).

(*b*) *Phosphate Liberation*

The determinations (given in table 1) were made simultaneously with those for oxygen consumption.

The data in table 1 show little consistency but there is a rapid (and apparently the maximum) liberation of phosphate phosphorus in the vicinity of 24 hours after death of the plankton; still later a rapid drop in rate of phosphate liberation occurs and it appears frequently that the rate of liberation is exceeded by the rate of consumption of phosphate (both from sea water and the decomposing plankton) by the growth of organisms associated with the decomposition. A similar liberation of phosphate has been observed by Cooper (1935); from his results we judge that about one third to one fourth of the amount of phosphate added as zoöplankton to sea water was set free during the first twelve hours, while an amount equivalent to that added as zoöplankton was liberated in about 6 days.

(*c*) *Free Fall Velocity of Decomposing Plankton*

The measurements (table 2) were made in sea water with a temperature range of 22° to 25°, a salinity range of 30.97 0/00 to 31.69 0/00, and a density (σ_t) range of 20.66 to 21.70. The actual density values for each measurement were calculated from temperature and salinity of the water. Each value in table 2 is the mean of ten to fifteen individual measurements.

In the treatment of this data we have assumed that the

TABLE 2

Experiment No. 1		Experiment No. 2		Experiment No. 3		Experiment No. 4		Experiment No. 5	
Age dead plankton	velocity cm./sec.	Age dead plankton	velocity cm./sec.	Age dead plankton	velocity cm./sec.	Age dead plankton	velocity cm./sec.	Age dead plankton	velocity cm./sec.
2^h	0.37	7^h	0.56	5^h	0.26	25^h	0.27	4^h	0.27
26^h	0.36	20^h	0.30	28^h	0.25	48^h	0.14	32^h	0.20
119^h	0.28	24^h	0.27	76^h	0.17	120^h	0.19	50^h	0.13
142^h	0.13	45^h	0.22			144^h	0.14	72^h	0.15
166^h	0.15	50^h	0.20						
191^h	0.15	68^h	0.12						
215^h	0.08	145^h	0.15						
316^h	0.07	170^h	0.09						
363^h	0.03	216^h	0.03						

rate of sinking of the particles of organic matter followed Stokes formula for the rate of settling (v) of small particles of radius, r, and density, ρ_0, under the influence of gravity, g, through a liquid (or gaseous) dispersing medium of density, ρ, and viscosity, μ, thus:[1]

$$v = \frac{2g}{9\mu} r^2(\rho_0 - \rho) \tag{2}$$

The formula stipulates that the particle should be spherical and since this condition is obviously not fulfilled in the case of organic particles we have used an "equivalent radius" such as has been introduced by Oden (Gripenberg, 1934). Since the size of the organic particle becomes smaller as decomposition proceeds the "equivalent radius" will become smaller with the increased state of the decomposition. Hence, at the outset an effort was made to determine r as a function of time by using the following procedure.

In the Stokes equation (2) the two unknown quantities were the density of the sinking particles, ρ_0, and their radii, r (the viscosity, μ, and density, ρ, of the dispersing medium are calculated from its temperature and salinity).[2] To determine ρ_0 the assumption was made that the density was the same for all particles studied and remained constant throughout the duration of the experiments (this is not strictly correct but appears necessary if the data are to be reduced). Then, by taking various pairs of free fall measurements obtained for the same age of the decomposing plankton, but from different experiments where the densities of the dispersing media were different, a number of pairs of simultaneous equations were obtained and solved for ρ_0. (This method of attack also makes use of the assumption that equal "equivalent radii" characterize equal ages of the various samples of decomposing plankton.) Finally, from the various individual values of ρ_0 a determination of the arithmetic mean gave, what was assumed to be, the most likely value for the density of the particles. Thus, we obtained from the data under consideration:

---

[1] For the material studied, it was observed that for any particle sinking through the water a practically constant velocity appeared to persist from the beginning.

[2] Viscosity of sea water was calculated for data given by Krümmel (1907), and density from Knudsen (1901).

$$\rho_{0_{\text{mean}}} = 1.02351$$

as the most likely value of ρ_0 to be used for calculation of the time variation of the equivalent radius, r. The mean density of the media in which the plankton decomposed was found to be 1.02109; thus, giving a density difference, between organic matter and the external media, of 0.00242 (a value which seems reasonable).

After insertion of the proper values in Stokes formula (2) the change of r with time was calculated (from data in table 2); the results are plotted in figure 2. The points show a linear decrease of r with time and the best straight line fit (by the method of least squares) has an equation of the form:

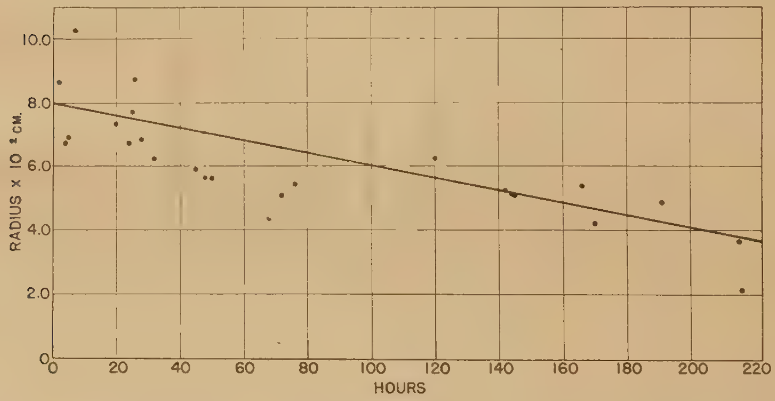


FIG. 2. Time variation of "equivalent radius," r, of decomposing animal plankton. The straight line trend has been fitted by the method of least squares.

$$r = r_0 - \beta t \tag{3}$$

where

$r_0 = 7.968 \times 10^{-2}$ cm. and $\beta = 5.356 \times 10^{-8}$ cm./sec.

The validity of the linear decline of r with time may be verified on the assumption that the rate of decomposition is probably proportional to the area of the particles, and if M be the mass of a particle and r its radius, then:

$$\frac{dM}{dt} = -kr^2$$

or

$$\frac{dr}{dt} = -\beta$$

and consequently:

$$r = r_0 - \beta t$$

The determination of r may be useful as an index for characterization of certain decomposition studies of this type. The value of β is calculated from results obtained at temperatures of 22° to 25°.

IV. Application of Experimental Results to the Ocean

Application of the foregoing experimental results to the sea is made, not with any intention of illustrating actual conditions in nature, but of showing how results of controlled laboratory experiments may be combined with an observed oceanographic set up in nature for the purpose of obtaining information on the laws regulating decomposition in the sea.

In the concluding part of this paper we calculated for an oceanic area, as represented by "Atlantis" station 1170 (14° 47′N, 40° 58′W), the change with depth of "equivalent radii" of particles of various initial sizes as they sink from the surface layer into the depths; and the time required for these particles to sink. The data are based on an assumed constant density of the particles corresponding to the known density of the water at a great depth (*e.g.* 1950 meters); the effect of eddying motion of the water is disregarded.

(*a*) *Distribution of Density at "Atlantis" Station 1170*

The vertical distribution of density (0–1950 meters) at "Atlantis" station 1170 (14° 47′ N., 40° 58′ W.) is illustrated by Fig. 3. Between depths of 1950 and 50 meters (taking the

z axis as positive upwards) the density distribution may be approximated by the hyperbola:

$$\sigma_t = 27.81 + \frac{z}{4.5889z - 92.4629 \times 10^4} \tag{4}$$

the distance z is measured in centimeters upwards from 1950

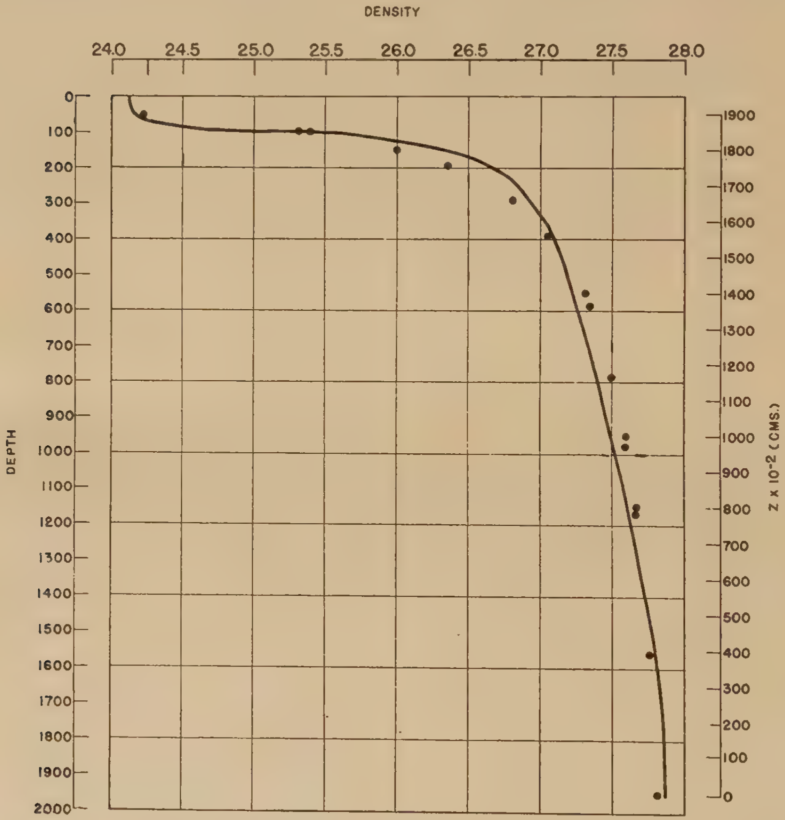


FIG. 3. Vertical distribution of density (σ_t) at "Atlantis" oceanographic station 1170 (14° 47′ N, 40° 58′ W). The points along the curve were calculated from the hyperbola $\sigma_t = 27.81 + \frac{z}{4.5889z - 92.4629 \times 10^4}$ where the z axis is positive upwards from 1950 meters.

meters. The values of σ_t determined by this equation for various values of z are indicated along the curve in Fig. 3.

(*b*) *Change in "Equivalent Radii" of Particles Sinking Through the Water Column at Station 1170*

We considered the sinking through the water column of organic particles originating in the upper 50 meter layer; the density of the particles corresponded to that of the water at a depth of 1950 meters ($z = 0$; $\sigma_t = 27.81$, $\rho_0 = 1.02781$) and remained constant during the sinking process.

The vertical distribution of density between $z = 0$ (1950 meters) and $z = 19.00 \times 10^4$ cms. (50 meters) at station 1170 is:

$$\sigma_t = 27.81 + \frac{z}{4.5889z - 92.4629 \times 10^4}$$

or

$$\rho = \rho_0 + \frac{z}{az + b},$$

where

$$\begin{aligned} \rho &= \sigma_t \times 10^{-3} + 1.00000, \\ \rho_0 &= 1.02781, \\ a &= 4.5889 \times 10^3, \\ b &= -\,92.4629 \times 10^7. \end{aligned}$$

From Stokes' law we have:

$$v = -\frac{dz}{dt} = \frac{2g}{9\mu} r^2 (\rho_0 - \rho)$$

where ρ_0 is the density of the sinking particle taken to equal 1.02781, and after substitution we have:

$$\frac{dz}{dt} = \frac{2g}{9\mu} r^2 \left(\frac{z}{az + b} \right)$$

also we may write:

$$\frac{dz}{dt} = \frac{dz}{dr} \cdot \frac{dr}{dt}$$

and since from equation (3)

$$r = r_0 - \beta t$$

or

$$\frac{dr}{dt} = -\,\beta$$

and

$$\frac{dz}{dt} = -\frac{dz}{dr}\beta$$

Substituting in the above equation we finally obtain:

$$\frac{dz}{dr} = \frac{k}{\beta}r^2\left(\frac{z}{az+b}\right) \tag{5}$$

where

$$k = -\frac{2g}{9\mu}$$

Integrating equation 5 gives the change of r with z or:

$$az + b \ln z = \frac{kr^3}{3\beta} + C \tag{6}$$

where C is the constant of integration to be evaluated. We now let h equal the distance above $z = 0$ at which depth the particles of initial radius r_0 begin to sink into the water. Hence, the conditions imposed on the above equation are when

$$z = h, \qquad r = r_0$$

or

$$C = ah + b \ln h - \frac{kr_0^3}{3\beta}$$

and after substituting for C we obtain as the final relation between r and z:

$$r^3 = r_0^3 + \frac{3\beta}{k}\left[a(z-h) + b \ln \frac{z}{h}\right] \tag{7}$$

The following constants were determined for the water column between $z = 0$ and $z = 19.00 \times 10^4$ cm. (1950 to 50 meters) at station 1170. $T°_{\text{mean}} = 7.45°$; $S\ 0/00_{\text{mean}} = 35.11$; $\mu_{\text{mean}} = 0.0151$ dyne-sec/cm.^{2}; from the experimental data $\beta = 5.356 \times 10^{-8}$ cm./sec., and finally $a = 4.5889 \times 10^3$, $b = -92.4629 \times 10^7$.

Since the effect of pressure on viscosity of the water is not known we have used a value of μ determined from the mean temperature and salinity of the water between 50 and 1950 meters (any further refinement appears to be superfluous). Furthermore, the value of β is assumed to be independent of temperature, this is probably not correct but in the light of our present knowledge is the best that can be done. We, thus, calculated the values:

$$k = -\frac{2g}{9\mu} = -1.4432 \times 10^4$$

$$\frac{\beta}{k} = -3.7112 \times 10^{-12}$$

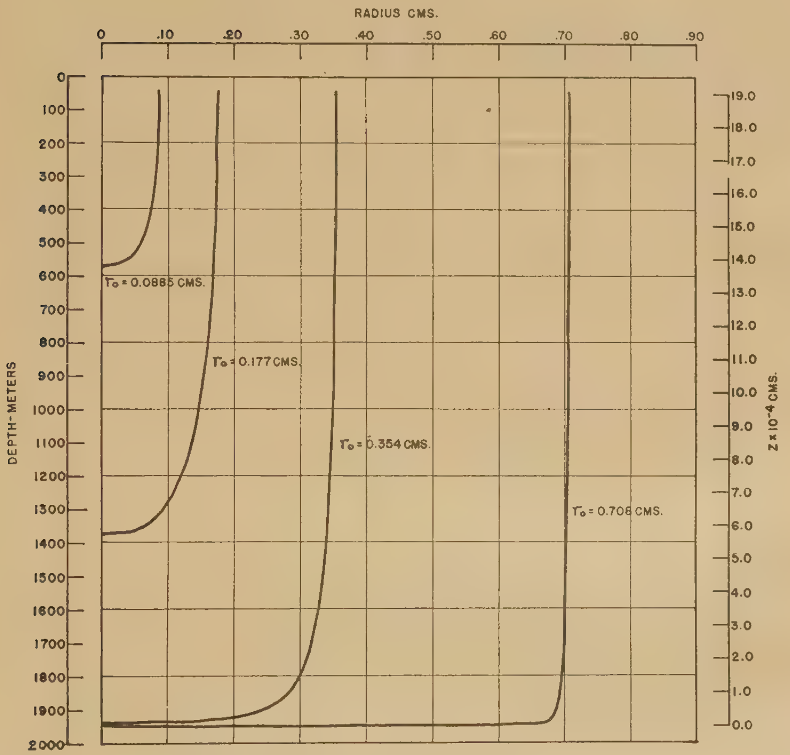


FIG. 4. Relation between the "equivalent radii" r and depth z for organic particles of four initial radii, r_0, when sinking through a water column represented by "Atlantis" oceanographic station 1170.

The relation between r and z is calculated for three values of initial radii (r_0) at 50 meters depth; these initial values are:

$$r_0 = 0.0885 \text{ cm.}$$
$$r_0 = 0.177 \text{ cm.}$$
$$r_0 = 0.354 \text{ cm.}$$
$$r_0 = 0.708 \text{ cm.}$$

and the results are graphically illustrated by Fig. 4. The value, $r_0 = 0.354$, is sufficient for the particle radius to theoretically become 0 at a distance of 10 meters ($z = 10^3$ cm.) above the level of its identical density. The curves illustrate that, if the particle is sufficiently large, it will approach asymptotically the level of equivalent density, whereas if the particle is completely broken down before it reaches this level (because of its small initial size) it will approach some level higher up in the water column in a similar manner.

(c) *Time Required for Particles to Sink Through the Water at Station 1170*

This calculation is based on the data of the previous section and the same assumptions and restrictions apply as formerly indicated. Thus, from equation (3) we have:

$$r = r_0 - \beta t$$

or

$$t_z = \frac{r_0 - r_z}{\beta} \tag{8}$$

where β is taken as 5.356×10^{-8} cm./sec. (1.928×10^{-4} cm./hour),[1] and from the value of r at any level z (Fig. 4) we obtain the time, under specified conditions, for organic particles having a density of 1.02781 and various initial equivalent diameters, as formerly, to sink from the fifty meter level into the depths. The results, plotted in Fig. 5, show that particles of larger equivalent radii sink faster and correspondingly remain for a longer time close to the level of similar density.

(d) *Phosphate Liberation and Oxygen Consumption of Organic Particles Sinking Through a Water Column*

Laboratory studies on decomposing organic material have shown that at the end of 24 hours after death there is a much greater decline in the rate of phosphate liberation than in the rate of oxygen consumption; and, if this be a true comparison of the relative activities of the two processes in nature, combination of these results with those of the time required for particles to sink through a water column suggests that relatively large quantities of phosphate may be liberated in the sea within the layer of photosynthesis. However, such a suggestion is merely tentative.

---

[1] A second determination of β recently made on decomposing zoöplankton at Bermuda (0–250 hours) gave a value (3.888×10^{-8}), close to that found for Woods Hole plankton.

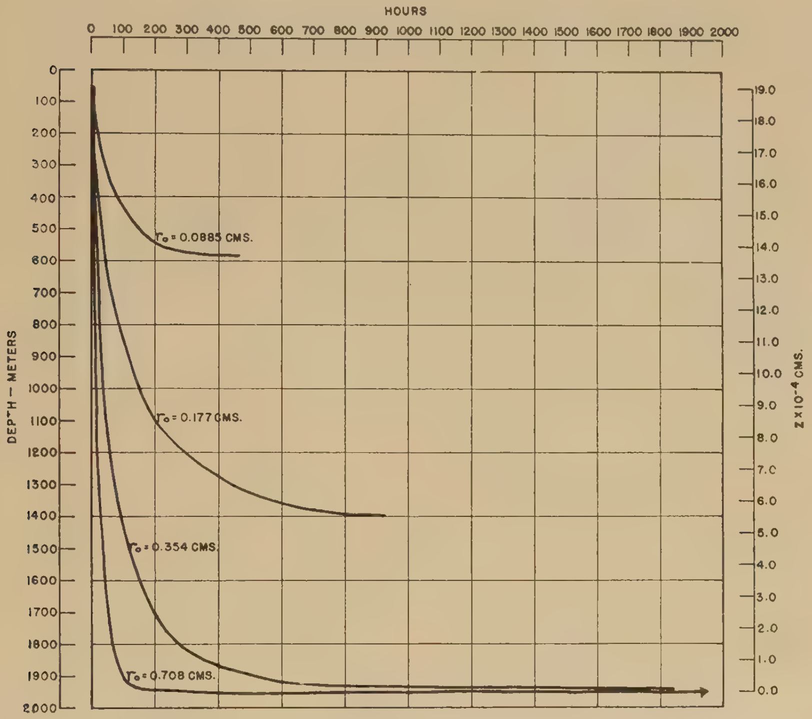


FIG. 5. Time required for organic particles of various initial radii, r_0, to sink into the water column represented by "Atlantis" oceanographic station 1170.

Since the consumption of oxygen by organic matter (as well as other reactions of decomposition) is, among other things, a function of the size of the body (page 473), the consumption equation obtained for the particular material studied cannot be generalized. However, a study of the time required for particles of various sizes to sink in a water column of variable density shows that unless these particles are of a relatively high density and of a relatively large "equivalent radius" much of the oxygen consumption will be confined to the upper part of the water column. From the data presented here we may generalize to the extent that since particles (having a density not greater than that of the bottom water) sinking through water of variable density will approach some level asymptotically, and if organic debris in the sea should be sufficiently homogeneous (as to density and "equivalent radius"), a stratum of maximum oxygen consumption may be conceived of as occurring in the sea. The position of such a stratum will depend on the density of the water as well as that of the organic debris, and its thickness on the homogeneity of the debris.

Conclusions

Application of the foregoing results to the ocean cannot be expected to show definitely what happens in nature. All sorts of possibilities exist, since not only is the relative importance of the size classes of organic matter in the sea unknown, but also the application of the results of controlled laboratory experiments to natural conditions can hardly be expected to illustrate with any degree of exactness a natural phenomenon.

It appears likely, however, that our results indicate, in a general way, the mechanism underlying certain of the biological activities in the ocean, in so far as these activities tend to alter the distribution of the non-conservative properties of the sea. One thing which appears noteworthy is that, since more biological activity apparently occurs in the upper levels of the ocean, it probably is the result either of a low density (similar to that of the upper levels) of the great mass of organic material, or else, in the case of a higher density, the great mass of organic matter has very small equivalent radii. However, in either case the physical conditions of organic matter in the sea need investigation to see if the equivalent radii and the density of the great mass of organic debris are sufficiently homogeneous so that biological activity may, in certain levels of the water column, offset the effects of dynamic processes and control the distribution of the non-conservative substances in the sea, or if, on the other hand, organic debris is so heterogeneous that the distribution of non-conservative substances is controlled largely by the horizontal and vertical circulation.

A somewhat similar question surrounds the origin of the minimum oxygen concentration and the minimum oxygen layer in the Atlantic. A recent study (Seiwell, 1937) has revealed that the minimum oxygen concentration in the western North Atlantic basin tends to occur at a density value (regardless of its depth) of $\sigma_t = 27.232 \pm 0.008$ which may suggest that this density value is somewhere near that of the great mass of organic matter. On the other hand, certain dynamic factors attached to such a situation prevent any rigid conclusion in favor of the biological argument as controlling the minimum oxygen concentration.

LITERATURE

Cooper, L. H. N. 1935. The Rate of Liberation of Phosphate in Sea Water by the Breakdown of Plankton Organisms. *Journal of the Marine Biological Association*, Vol. XX, No. 2, pp. 197–200.

Gripenberg, Stina. 1934. A Study of the Sediments of the North Baltic and Adjoining Seas. *Havsforsknings-institutes Skrift*, No. 96. 231 pp.

Knudsen, Martin. 1901. Hydrographical Tables. Copenhagen. 63 pp.

Krümmel, Dr. Otto. 1907. Handbuch der Ozeanographie, Band I. Stuttgart. 526 pp.

Seiwell, H. R. 1934. The Distribution of Oxygen in the Western Basin of the North Atlantic. *Papers in Physical Oceanography and Meteorology*, Vol. III, No. 1. 86 pp.

Seiwell, H. R. 1935. The Cycle of Phosphorus in the Western Basin of the North Atlantic. 1. Phosphate Phosphorus. *Papers in Physical Oceanography and Meteorology*, Vol. III, No. 4. 56 pp.

Seiwell, H. R. 1937. The Minimum Oxygen Concentration in the Western Basin of the North Atlantic. *Papers in Physical Oceanography and Meteorology*, Vol. V, No. 3. 24 pp.

Waksman, Selman A., and Renn, Charles E. 1936. Decomposition of Organic Matter in Sea Water by Bacteria. III. Factors Influencing the Rate of Decomposition. *Biological Bulletin*, Vol. LXX, No. 3, pp. 472–483.

Contribution No. 154

U. S. TREASURY DEPARTMENT
COAST GUARD

OCEANOGRAPHY

EXCERPT FROM

INTERNATIONAL ICE OBSERVATION AND ICE PATROL SERVICE IN THE NORTH ATLANTIC OCEAN

Season of 1936

UNITED STATES
GOVERNMENT PRINTING OFFICE
WASHINGTON : 1938

OCEANOGRAPHY [1]

By Floyd M. Soule

The *General Greene* departed from Boston on March 31 and proceeded to St. John's where she arrived April 4. After supplies and fuel had been taken on, departure was taken from St. John's on April 8 for the purpose of making a current survey of the region immediately eastward of the Grand Banks from the latitude of Flemish Cap southward to about latitude 41° N. The work of collection of data began on April 9 at station 2048, and was completed at station 2117 near the Tail of the Grand Banks on April 19, after 70 stations had been occupied. The resulting current chart, figure 25, was then constructed and delivered aboard the *Pontchartrain* 19 hours after the last station had been completed. The *General Greene* then proceeded to St. John's, arriving there on April 21.

On May 6 the *General Greene* departed from St. John's for the purpose of making a second current chart. The area surveyed was similar to that covered by the April map. The work of collection of data began on May 7 at station 2118 and was completed at station 2187 on May 17, after 70 stations had been occupied. The current map made from this survey was completed within 24 hours after the final station but delivery aboard the *Pontchartrain* could not be effected until the morning of May 19 because of rough weather. After the current map, figure 26, had been delivered, the *General Greene* returned to St. John's where she arrived on May 19.

Departure was taken from St. John's on June 1 to make a third current survey. In response to a dispatch from the commander of the International Ice-Patrol force the program was so planned that the work of collection would take about 6 days. As it was believed that the greatest amount of information could be obtained in the stipulated time from a survey of the area between about latitudes 43° and 46° N., east of the Grand Banks, the work of collection was begun on June 2 at station 2188 and was completed at station 2234 on June 8 after 47 stations had been occupied. The resulting current chart is shown in figure 27. As the Ice Patrol was discontinued for the season on June 9, the ice-observation officer, Lt. G. Van A. Graves, transferred to the *General Greene* which then proceeded to St. John's.

A total of 187 stations was thus occupied during the Ice-Patrol season. An additional 30 oceanographic stations were occupied on

---

[1] Contribution No. 154 of the Woods Hole Oceanographic Institution.

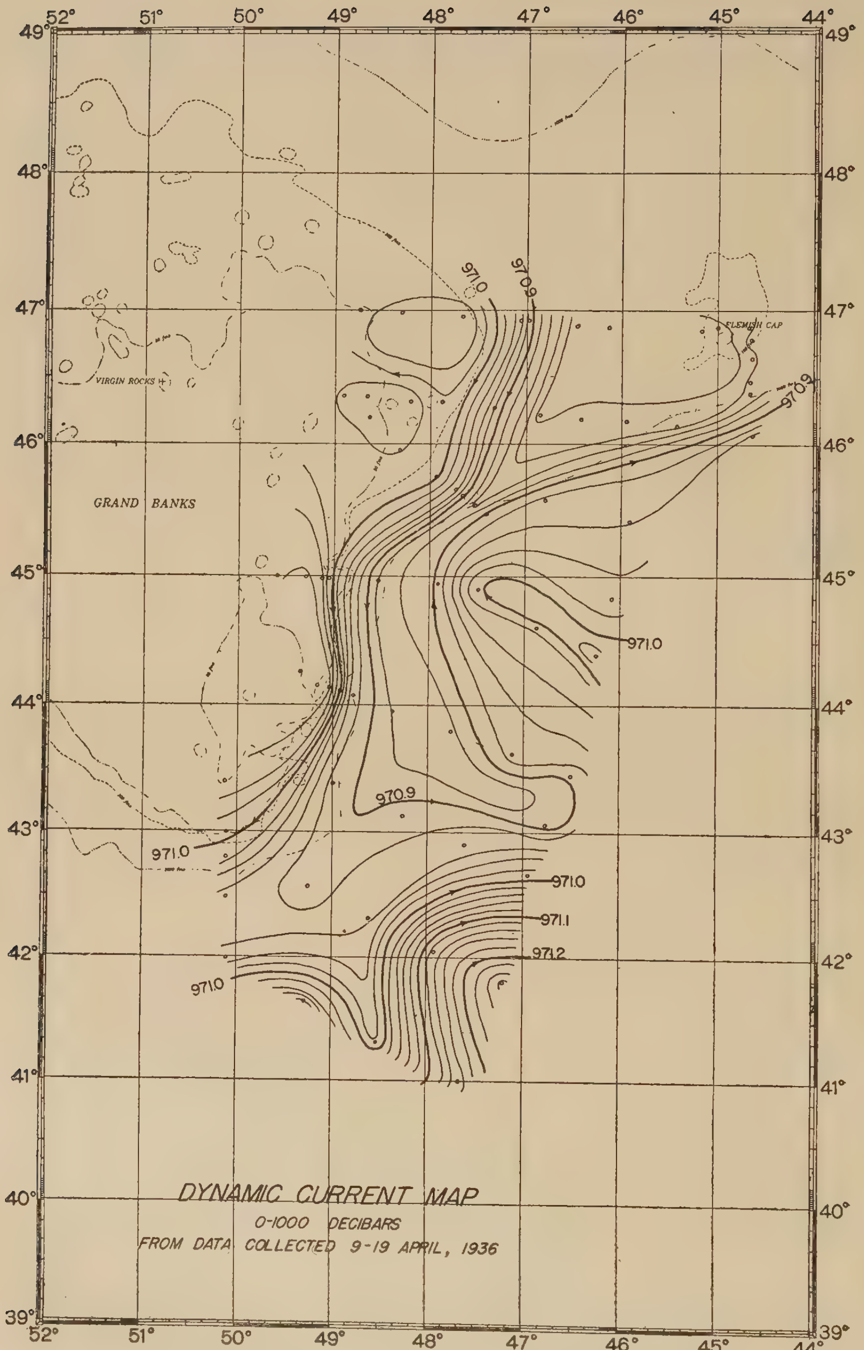

52°
51°
50°
49°
48°
47°
46°
45°
44°
49°
48°
47°
46°
45°
44°
43°
42°
41°
40°
39°
VIRGIN ROCKS
GRAND BANKS
FLEMISH CAP
971.0
970.9
971.0
970.9
971.0
971.0
971.1
971.2
971.0
DYNAMIC CURRENT MAP
0-1000 DECIBARS
FROM DATA COLLECTED 9-19 APRIL, 1936

Figure 25.—Dynamic current map, from data collected April 9–19, 1936.

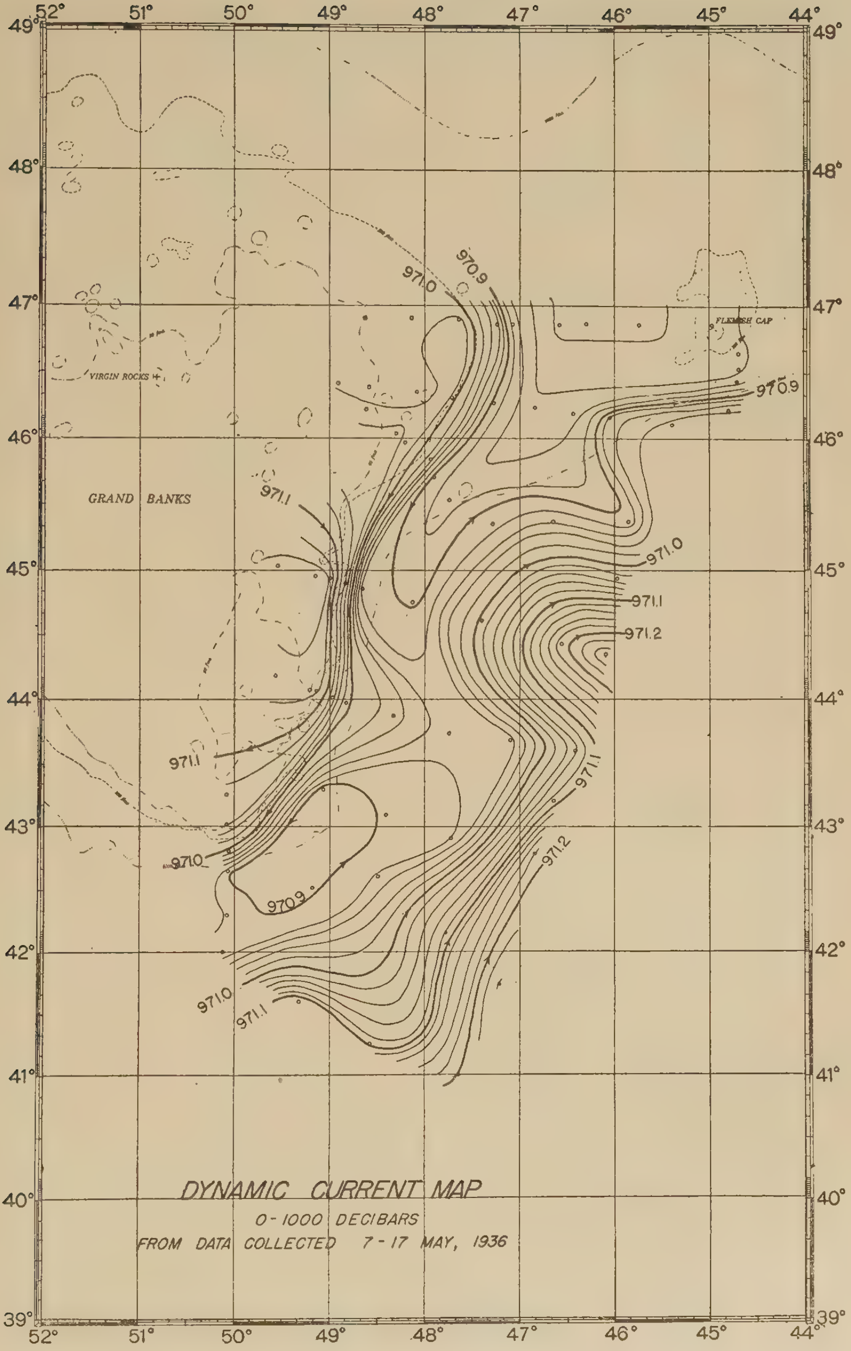

52°
51°
50°
49°
48°
47°
46°
45°
44°
39°
40°
41°
42°
43°
44°
45°
46°
47°
48°
49°
VIRGIN ROCKS
GRAND BANKS
FLEMISH CAP
970.9
971.0
971.1
971.2
DYNAMIC CURRENT MAP
0-1000 DECIBARS
FROM DATA COLLECTED 7-17 MAY, 1936

Figure 26.—Dynamic current map, from data collected May 7-17, 1936.

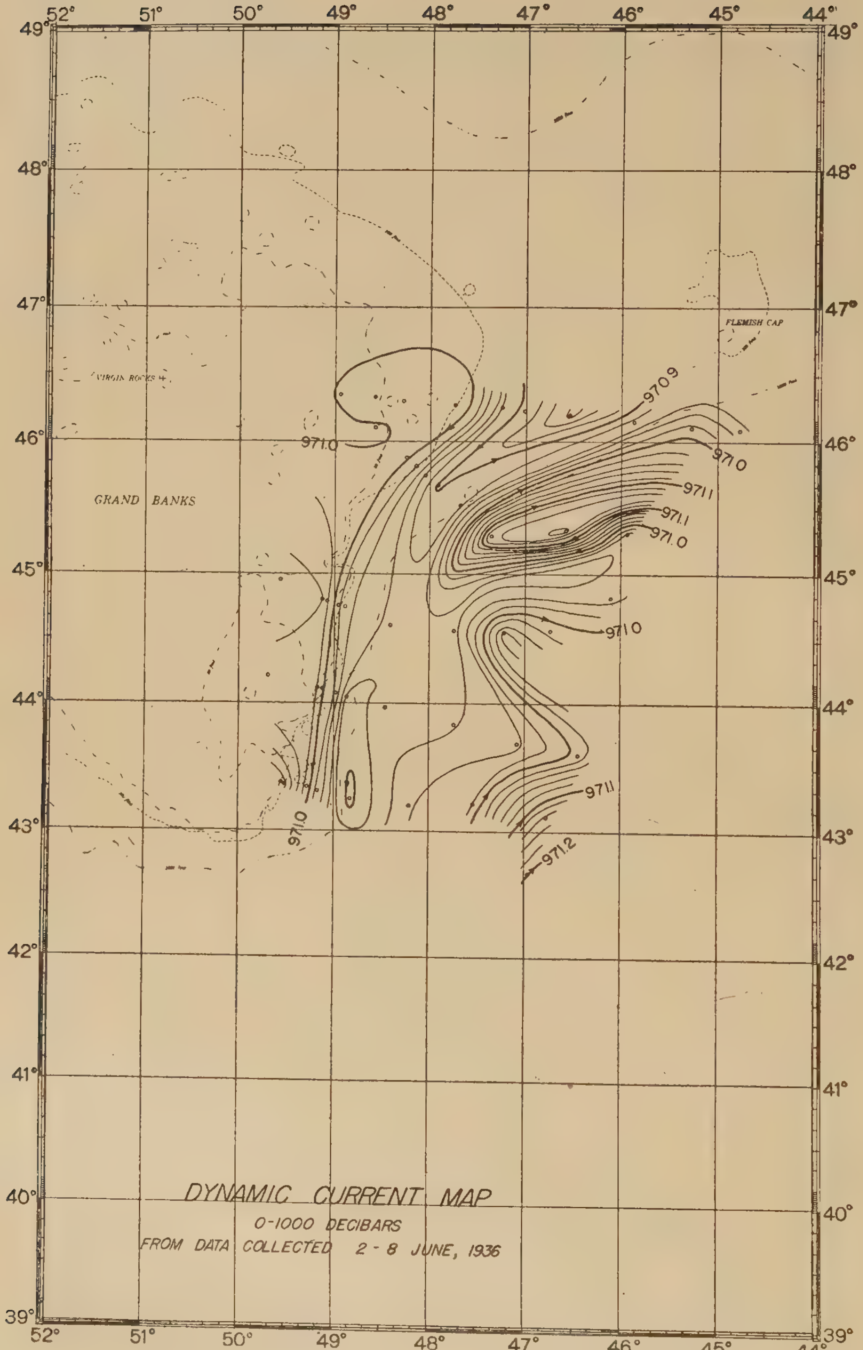

52°
51°
50°
49°
48°
47°
46°
45°
44°
49°
48°
47°
46°
45°
44°
43°
42°
41°
40°
39°
FLEMISH CAP
VIRGIN ROCKS
GRAND BANKS
970.9
971.0
971.0
971.1
971.1
971.0
971.0
971.1
971.0
971.2
DYNAMIC CURRENT MAP
0-1000 DECIBARS
FROM DATA COLLECTED 2 - 8 JUNE, 1936

FIGURE 27.—Dynamic current map, from data collected June 2–8, 1936.

an abbreviated post-season cruise in the Labrador Sea. These 30 stations were occupied between June 20 and June 26 and were disposed in the form of two sections, one extending from the vicinity of South Wolf Island, Labrador, to Cape Farewell, Greenland, and the other from 60°09′ N., 51°15′ W., to the mouth of Arsuk Fjord, Greenland. The surface currents indicated by the measurements at these stations are shown in the dynamic topographic chart, figure 28. The temperature and salinity data collected at the 217 oceanographic stations

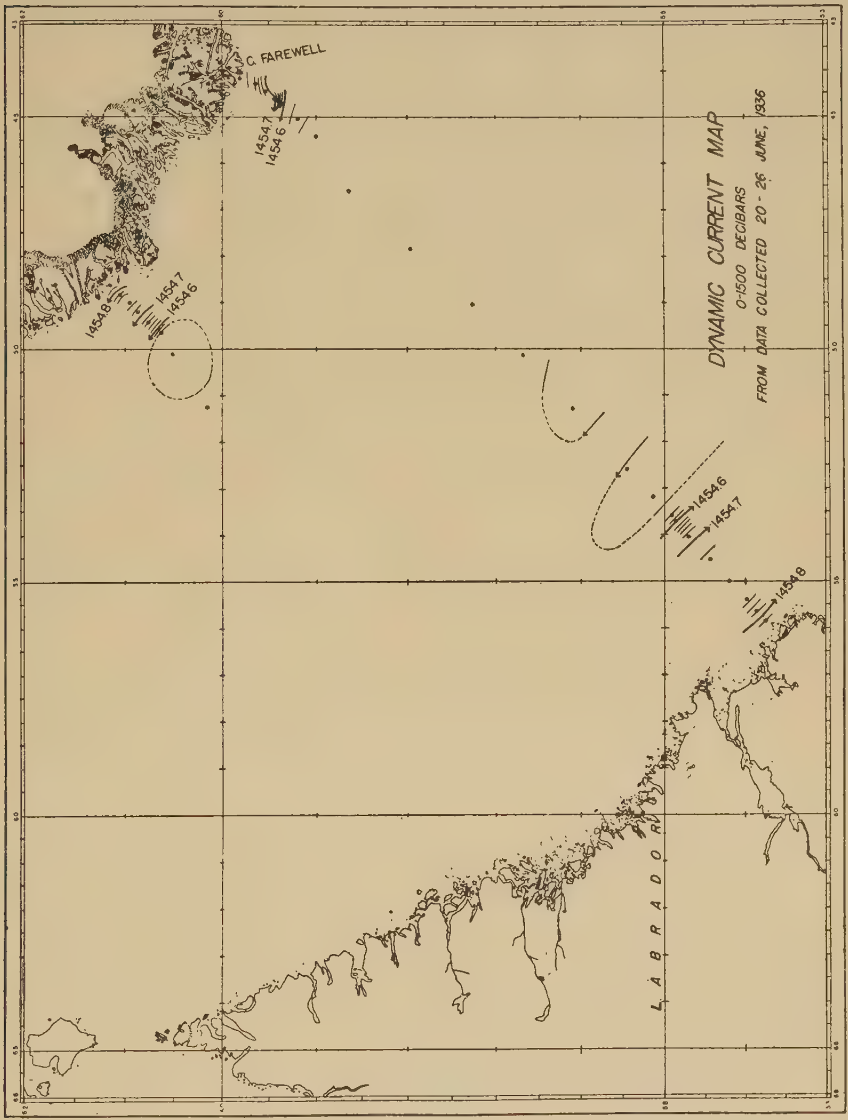

C. FAREWELL
14547
14546
14548
14547
14546
DYNAMIC CURRENT MAP
0-1500 DECIBARS
FROM DATA COLLECTED 20 - 26 JUNE, 1936
14546
14547
14548
LABRADOR

FIGURE 28.—Dynamic current map, post-season cruise, June 20-26, 1936.

occupied during the season and on the post-season cruise are presented in the oceanographic table in this bulletin.

On the post-season cruise 295 sonic soundings were made with the fathometer. These have been corrected for sounding velocity by means of the concurrently collected temperature and salinity data in accordance with the temperature-salinity-pressure-velocity relations given in the British Admiralty tables (H. D. 282). The corrected soundings have been tabulated and forwarded to the United States Hydrographic Office and to the International Hydrographic Bureau.

During the ice season, and in continuation of cooperation with the Newfoundland Fisheries Research Laboratory at Bay Bulls, abstracts of temperatures and salinities measured were forwarded to that laboratory promptly upon the return of the *General Greene* to St. John's at the conclusion of each survey. Other incidental data collected on the *General Greene* consisted of barograms and sea-water surface thermograms. The Ice Patrol has photographed the glacier front in Arsuk Fjord, Greenland, during the summers of 1928, 1931, 1933 and did so again in 1936. This year the various distances of retreat and advance were measured by means of numerous horizontal sextant angles taken from both ends of a 600-foot base line. The results of these measurements have been forwarded to the chairman of the committee on glaciers of the American Geophysical Union.

The equipment and methods of measurement were the same as in 1935. Routine salinity bridge measurements were performed by the oceanographer's assistants, Bernard S. Loebig, yeoman, first-class; Edwin H. MacDonald, quartermaster, third-class; and surfman James F. Flannery. The first-named performed the calibration titrations.

At the 187 stations occupied during the season serial observations of temperature and salinity extended to depths of between 1,000 and 1,400 meters where the depth of water permitted. The levels from which it was attempted to obtain measurements were 0, 25, 50, 75, 100, 150, 200, 300, 400, 600, 800, 1,000, and 1,400 meters. On the post-season cruise the observations were carried to as near the bottom as practical at all stations, the nominal depths of observations being similar to those listed above from the surface down to 1,000 meters and at 500-meter intervals below 1,000 meters.

Both during the season and on the post-season cruise the thermometers, which were used in pairs, were occasionally shifted with respect to each other so that each thermometer was eventually paired with several other thermometers, thus furnishing a check against the possibility of any thermometer or thermometers suffering a change of calibration or ceasing to function properly during the period of observations. A total of 1,434 such comparisons were investigated. Probable differences between the corrected readings of the pair of thermometers were computed for each group. These probable differences varied between 0.003° and 0.014° C. and the probable difference for the entire 1,434 comparisons was 0.008° C. It is therefore considered that the observed temperatures are accurate to 0.01° C.

The current maps prepared during the season were made following the procedure used in 1935, the season's maps being referred to the 1,000 decibar surface. The current map representing conditions found on the post-season cruise is referred to the 1,500 decibar surface.

The dynamic current map for April, figure 25, shows the Labrador Current to be somewhat subnormal in surface velocity in the northern part of the map, but having unusual width. In latitudes 44° to 45° its flow is augmented by the Grand Banks whorl which is frequently a characteristic of the circulation in this region. Another feature less frequently encountered is the slow but definite clockwise whorl near the eastern edge of the Banks in about latitude 47° north. Its effect is to set icebergs in onto the Banks; a natural tendency here where the shoaling bottom below the Labrador Current probably exerts some influence in a deflection toward the right. A part of the Labrador Current will be seen to recurve northeastward north of latitude 45°. Although the measurements do not extend to the westward of about longitude 50° west it is evident that south of the Tail of the Banks the Labrador Current continues west and south before recurving eastward. Gulf Stream water is to be seen in the more rapidly flowing currents at the southern edge of the map.

From figure 26 it will be seen that the Labrador Current decreased in width and increased in velocity from April to May. The clockwise whorl noted in the April map near the eastern edge of the Banks in about latitude 47° north joined the Banks whorl centered near 44°30′ N., 49°30′ W. This Banks whorl contributed water off the Grand Banks to what would seem at first glance to be the Labrador Current. However, it will be seen that that portion westward of about the 971 isobath was part of the Banks whorl and cannot be considered part of the ice-bearing Labrador Current. Much of the latter continued to recurve northeastward between latitudes 47° and 44° north although a part still continued to the Tail of the Banks. The Gulf Stream margin weakly evidenced on the eastern edge of the April map between latitudes 44° and 45° north had intruded with strength and began the pinching off of the Labrador Current and resulted in closing off and partly assimilating the cold-water pool near the Tail of the Grand Banks.

The June current map, figure 27, shows that the Labrador Current was much weakened in velocity, while the intruding Gulf Stream salient had made no further westward progress from the situation shown in figure 26. What has been drawn as a Gulf Stream salient between latitudes 45° and 46° north may be a closed whorl in the nature of clockwise eddy separated from the main stream. If it is indeed such an eddy the possibility is suggested that it was present in all three maps, moving in a northeasterly direction from near the lower edge of figure 25 to the middle eastern edge of figure 26 to the upper eastern edge of figure 27. The observations do not extend far enough to the eastward to tell. If this is such an eddy it is probably the first time that one of this magnitude has been surveyed during 3 successive months. The fact that the entire area of the eddy was not investigated makes it impossible to arrive at any accurate conclusion as to the energy involved. However, it is interesting to note its persistence over a period of about 2 months. Throughout the season the maps indicated a possible avenue of southward transport for bergs, so that the discontinuation of the Ice Patrol for the season had to be made on the basis of lack of ice rather than on the basis of currents which would not permit the drift of ice into the steamer lanes.

In United States Coast Guard Bulletin No. 19, Part 2, the authors of that paper briefly discussed the question of an annual cycle in the strength of the Labrador Current in the Grand Banks sector in view of the popular but unsupported opinion that that current experiences a "spring freshet" approximately coincident in time with the peak of the iceberg season. Because of the paucity of comparable data then available it could only be concluded that if such a cycle did exist it was masked by the great variations from year to year. Since the preparation of that report further work on this question has been done and another year's observations are available. In view of the facts that the variations from year to year are large and the number of available data small it was realized that in order to investigate the annual cycle properly it would be necessary to have a succession of measurements for each season considered and that random measurements from various years could not be combined without overweighting averages with the characteristics of those particular years.

We have to discuss here some of the same sections discussed in United States Coast Guard Bulletin No. 19, Part 2, in the chapter on the Grand Banks sector, and for the convenience of those who wish to refer to the above publication we shall retain the previous section designations which are: Section T, running southeasterly from about latitude 46°20′ N., longitude 49°00′ W.; section U, running east and west at about 45° N.; and section W, a north and south section at the Tail of the Grand Banks in about 50° W. The Labrador Current passing section T may be regarded as coming entirely from more northerly regions. The southerly flow past section U represents the Labrador Current of section T plus the contribution of the Grand Banks whorl and minus the usually small amount of Labrador Current which has recurved northeastward between sections T and U. The westerly current through section W represents that part of the flow past section U which has not recurved although occasionally augmented by the borders of a closed counterclockwise eddy south of the Tail of the Grand Banks.

Sections T and U have been occupied during the months of April, May, and June of each of the years 1934, 1935, and 1936. Section W has been occupied during April and May of each of these 3 years and in June 1934. The volume of flow, the mean temperature, and the minimum temperature have been investigated for each occupation of these sections and the results are tabulated below.

Table 1.—*Showing volume of flow in million cubic meters per second, mean temperature in °C, and minimum temperature in °C, of the Labrador Current in the Grand Banks region*

	Section T				Section U				Section W			
	1934	1935	1936	Average	1934	1935	1936	Average	1934	1935	1936	Average
April:												
Vol	1.8	2.1	1.86	1.92	3.48	3.7	7.20	4.79	1.17	1.08	3.13	1.79
Mean Temp	1.53	1.67	0.98	1.39	1.11	2.0	2.31	1.81	1.19	2.72	2.61	2.17
Min. Temp	−1.66	−1.71	−0.75	−1.37	−1.37	−1.66	−0.82	−1.28	−1.15	−1.12	0.02	−0.75
May:												
Vol	1.5	4.1	3.23	2.94	3.11	5.92	6.69	5.24	1.63	3.87	8.78	4.76
Mean Temp	2.6	2.85	1.83	2.43	1.56	0.98	1.06	1.20	1.07	1.47	2.85	1.80
Min. Temp	−1.72	−1.56	−0.43	−1.24	−1.70	−1.24	−0.94	−1.29	−1 58	−1.02	0.08	−0.84
June:												
Vol	1.5	2.71	3.15	2.44	0.84	4.46	3.90	3.07	0.86	------	------	------
Mean Temp	3.3	2.06	2.90	2.75	1.32	1.75	3.14	2.07	4.35	------	------	------
Min. Temp	−1.70	−1.50	−1.47	−1.56	−1.65	−1.28	−1.23	−1.39	1.68	------	------	------

An inspection of the above table shows that although the mean temperature and the minimum temperature do not show very consistent trends, the volume of flow does. The volume-time relation is shown graphically in figure 29 for each ice season and for each of the sections T, U, and W. Smooth curves have been drawn and although the exact course of any curve between points is somewhat conjectural the curves illustrate that there is a striking uniformity in the suggestion of a seasonal maximum volume of flow about the middle of May. At least they do not preclude the existence of such a maximum. Curves are also shown representing the 3-year average for each of the sections. It will be noted that the volume of flow was above this average throughout the season of 1936 at each of the sections. As the curves in figure 29 have been drawn the time of the maximum is slightly earlier for section U than for either sections T or W. It is doubtful that this time difference is significant in view of the small number of data considered. It may nevertheless be real and if so is connected with the Grand Banks whorl. It is possible that this whorl, which is centered near the shoalest part of the Grand Banks, is accelerated by vernal warming just prior to the arrival of the true freshet from north of the Grand Banks.

Further inspection of table 1 shows considerable variability in the mean temperature of the Labrador Current. A much greater constancy is shown in the minimum temperature. Comparison of the values for the season of 1936 with those of the 3-year average shows that at section T the mean temperature was colder than usual during the months of April and May and slightly warmer than usual in June. As stated above, this section is regarded as most nearly indicative of unmodified Labrador Current conditions of the three sections considered. Taking all sections, the mean temperature was only 0.26° C. warmer for the entire season than average. However, the minimum temperature was warmer than average for each section throughout the season, and taking all occupations of all sections for 1936 the minimum temperature was 0.52° C. warmer than average.

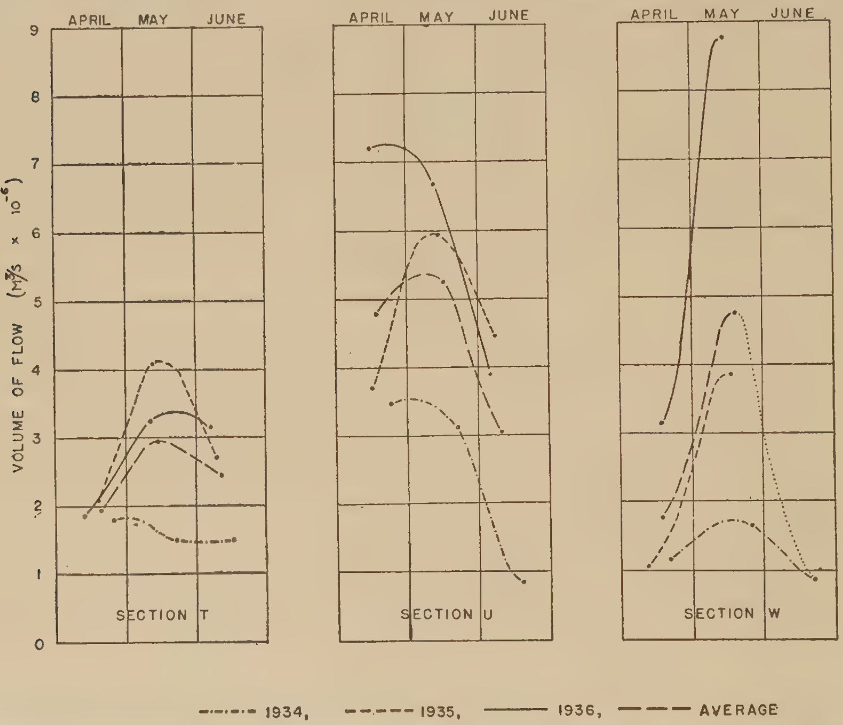


FIGURE 29.—Variations in volume of flow of the Labrador Current in the Grand Banks sector during the ice seasons of 1934, 1935, and 1936.

As has been shown by Smith, Soule, and Mosby in United States Coast Guard Bulletin No. 19, Part 2, the Labrador Current is composed of Baffin Land Current and West Greenland Current in the proportions of about 2 to 3, the Baffin Land component supplying the inshore, minimum temperature band of the Labrador Current. In 1935, both in March and in August, the West Greenland Current rounding Cape Farewell, Greenland, was flowing at about double its normal volume. As a part of the West Greenland Current enters Baffin Bay across Davis Strait Ridge it is probable that this excessive rate of flow was communicated to the Baffin Land Current, with the resultant increase in volume of flow and minimum temperature noted in the Labrador Current in the Grand Banks sector during the season of 1936.

The significance of such a flood of the West Greenland Current in relation to the quantity of berg ice subsequently appearing in the Grand Banks region is as yet obscure. Two oppositely direct effects are at once suggested. The greater heat transfer northward along the Greenland coast will tend to release accumulations of pent-up bergs. On the other hand warmer temperatures should hasten the disintegration of the bergs during their long travel to the Grand Banks. The first effect of the flood in question was probably to sweep the American side clean of bergs in 1935 and to free large numbers of bergs along the Greenland side. The latter bergs probably spent the winter of 1935–36 in the vicinity of Melville Bay and can be expected to winter near Cape Dier 1936–37 appearing in the Grand Banks region during the season of 1937. It will be of interest to note whether the higher temperatures during the interval of travel, 1935–37, will outweigh, through more rapid disintegration of the bergs, the effect of a greater number of bergs freed and result in a net increase or decrease of berg ice on the Banks as reflected in the discrepancy between the actual berg count and the number forecast on purely meteorological considerations.

Temperature-salinity relations are frequently helpful in tracing and identifying water masses. In the region of the Grand Banks, where two major ocean currents of different characteristics (the Labrador Current and the Atlantic Current) closely approach each other, we are concerned chiefly with the fluctuations in the boundary between them and the departures of that boundary from its normal position. The data accumulated during the seasons of 1934, 1935, and 1936 have been examined and salinity anomalies determined. The anomalies are departures from the T–S relation for the western North Atlantic above 4° C, and for the Chesapeake Bay-Bermuda section between 2° and 4° C, as shown by Iselin (Papers in Phys. Oceanog. and Met. M. I. T. and W. H. O. I., vol. IV, no. 4, pp. 41 and 87. Aug. 1936. Cambridge). Examination shows a characteristic tongue of maximum salinity anomaly at intermediate depths of about 800 meters in the Atlantic Current, grading off to characteristic negative anomalies in the Labrador Current. The position of the projection, on a horizontal surface, of the zero anomaly line in the axis of maximum anomaly has been taken as a criterion of the boundary between Atlantic Current water and Labrador Current water. Figure 30 shows the course of this zero anomaly line for each of the nine surveys carried out during the three year period. Inspection of these lines showed five characteristic salients of Atlantic Current water and four intermediate salients

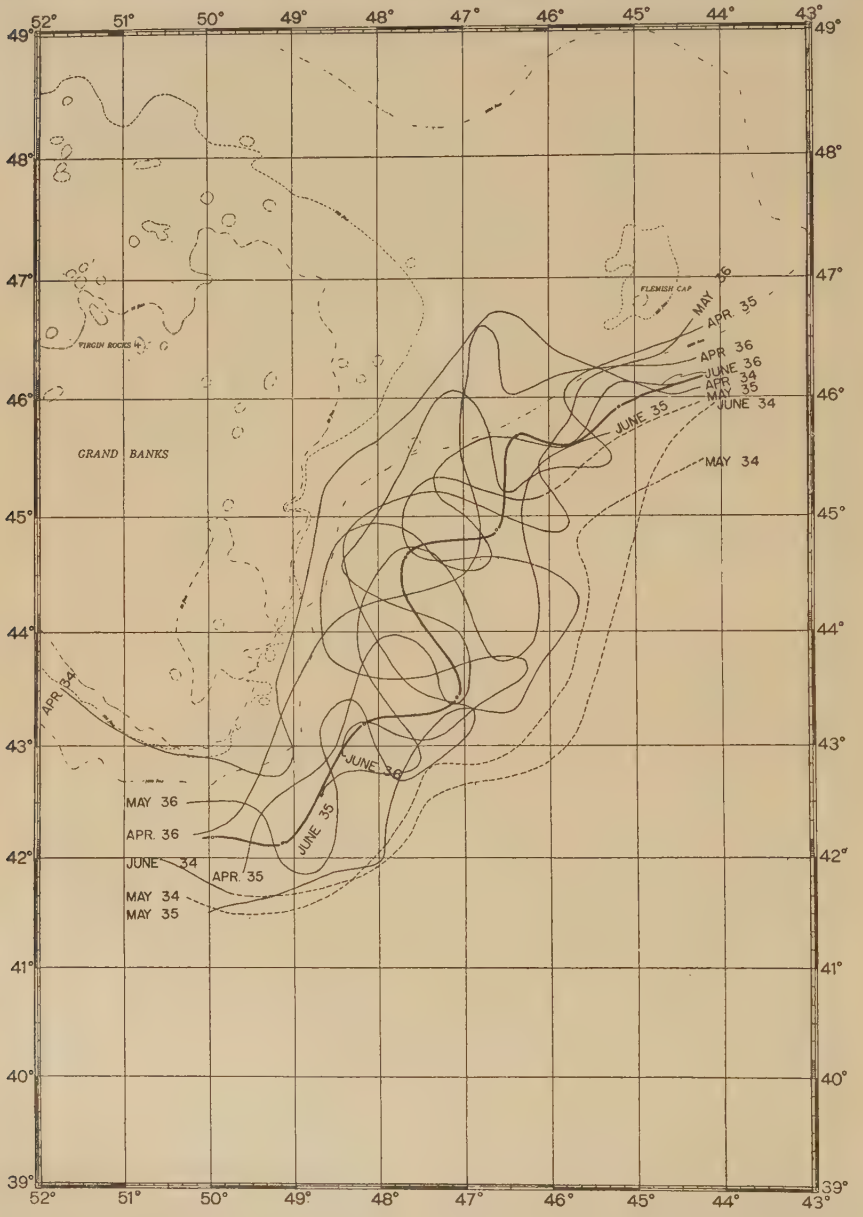

52°
51°
50°
49°
48°
47°
46°
45°
44°
43°
49°
48°
47°
46°
45°
44°
43°
42°
41°
40°
39°
VIRGIN ROCKS
GRAND BANKS
FLEMISH CAP
MAY 36
APR. 35
APR 36
JUNE 36
APR 34
MAY 35
JUNE 34
JUNE 35
MAY 34
APR. 34
JUNE 36
JUNE 35
MAY 36
APR. 36
JUNE 34
APR. 35
MAY 34
MAY 35

Figure 30.—Boundary between Labrador Current water and Atlantic Current water as indicated by the course of the zero anomaly line bounding the intermediate salinity anomaly maximum. Individual surveys and average, 1934–36.

of Labrador Current water from the Tail of the Grand Banks to Flemish Cap. The mean positions of these nine points have been computed and a smooth curve drawn through them to represent the average course of the zero anomaly line. This is the heavy line in figure 30. Thus it will be seen that in 1936 the April survey showed greater than normal intrusion of Atlantic Current water, with May and June not much different than normal. It is also possible that the early season departure from normal was the result of the above-mentioned preponderance of the West Greenland Current component in the make-up of the Labrador Current through alteration of the Baffin Land Current character.

The usefulness of such a method of comparing the results of any survey with average conditions is not impaired by any doubt as to the validity of the T–S relationship used as a reference. Such a doubt does exist and possibly the resulting anomaly maximum is more apparent then real. The T–S relation used as a reference below 4° C. has in it a hump of lower salinity centered at about 3° to 4° C. A smoother curve would require a maximum increase of about 0.02‰ salinity at about 3.5° C. Such an amount would reduce but not erase the anomaly maximum referred to above. This anomaly maximum, coming as it does in depths of about 800 meters, falls within the temperature range of about 3° to 4° C.

In the area from which the T–S relationship in question was derived, namely from Chesapeake Bay to Bermuda, the temperature range of 3° to 4° C. is at a depth of about 1,600 to 3,000 meters. The suggestion is that this water has, as one of its components, water from some region where a less positive (or more negative) salinity anomaly is characteristic such as the bottom water of the Labrador Sea. The drainage of such water out of the Labrador Sea into the Western Atlantic Basin is discussed farther on under the heading "Bottom temperature."

POST-SEASON CRUISE, 1935

As described in United States Coast Guard Bulletin No. 25, a post-season cruise was made in 1935 to the region of the Labrador Sea from about the fiftieth parallel to a line between Cape Farewell, Greenland, and South Wolf Island, Labrador. The station table data, the resulting dynamic topographic map of the surface with respect to the 1,500 decibar surface, and a bathymetric map of the area covered have already been published in that bulletin. Parts of the data have been drawn upon in the preparation of Bulletin No. 19, Part 2. Some phases of the survey, however, have been mentioned but briefly and will be taken up here.

Horizontal distribution of temperature and salinity.—The horizontal distribution of temperature and salinity in the upper layers has been illustrated by composite maps of those variables at 100 meters, published as figures 127 and 128 of Bulletin No. 19, Part 2. At this level both temperature and salinity show the presence of the major surface streams, the Irminger and Atlantic Currents being characterized by warm and salty water and grading off inshore to the colder fresher water of the East Greenland and Labrador Currents. At a depth of 1,000 meters the temperature and salinity distribution, as shown in figures 31 and 32, still is characterized by relatively warm and salty water beneath the Irminger and Atlantic Currents. Figures 33 and 34, the temperature and salinity at 1,500 meters, show that although beneath the deeper-flowing Atlantic Current the higher temperatures and salinities persist, around Cape Farewell this level is below the effect of the Irminger Current and we find typical intermediate water of the Labrador Sea [2] except in the southern part of the region.

At 2,000 meters we approach the lower limit of the intermediate water. Figures 35 and 36 give the temperature and salinity distribution at this level and show the central portion of the area to be filled with intermediate water while the margins, except beneath the Atlantic Current, show the transition toward deep water character with lower temperature. Another indication of the transition to deep water is the 34.94‰ salinity line near the eastern edge of the area.

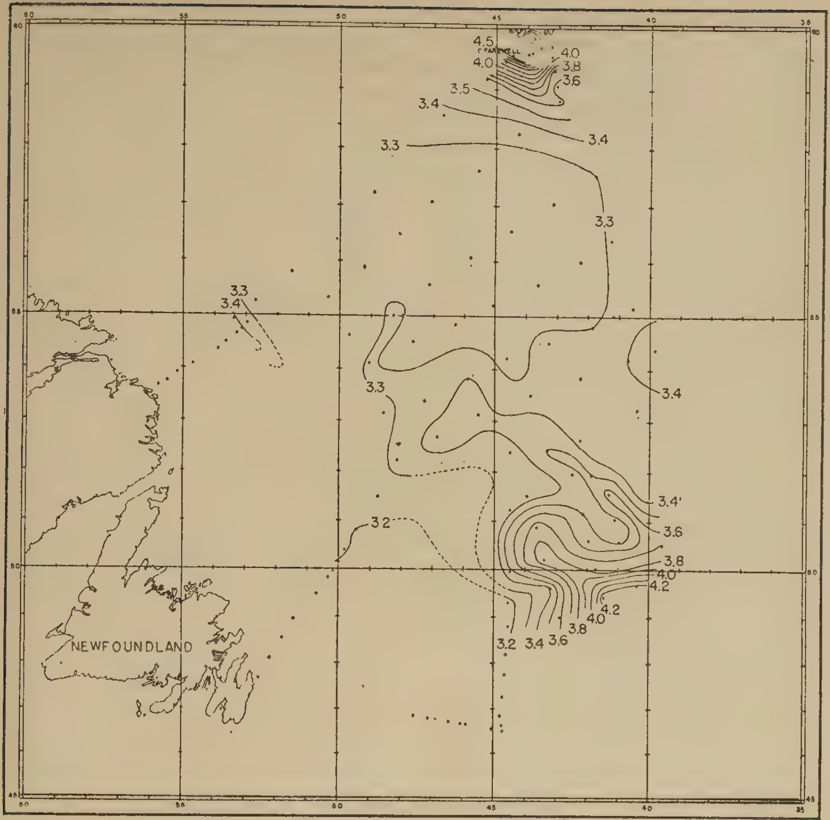
Figures 37 and 38 represent the temperature and salinity distribution at 2,500 meters. This level is in the upper part of the deep water, the margins showing lower temperature than the central part and the 34.94‰ isohalines delineating the upper portions of the salinity maxima which characterize the deep water. Figures 39 and 40 show the temperature and salinity at 3,000 meters and seem to be well centered in the deep water. In figure 40 the 34.96‰ salinity line and its surrounding 34.94‰ line indicate a salinity maximum probably originating in the northeastern arm of the Labrador Basin. The 34.94‰ area between Labrador and Cape Farewell probably had its origin in the northwestern arm of the Labrador Basin. Attention is called to the opinion set forth in United States Coast Guard Bulletin No. 19, Part 2, that these salinity maxima of the deep water of the Labrador Sea are formed intermittently and follow the general cyclonic movement of the deep water northward along the west Greenland side of the basin and southward along the American side.

Figures 41 and 42, the temperature and salinity at 3,500 meters, show the transition from deep water to bottom water with indications of the coldest water moving out of the Labrador Basin along the American side. This direction of motion of the bottom water is further indicated in figures 43 and 44 which give the temperature and salinity at 4,000 meters.

Circulation within the stratosphere.—Observation and experience has shown that the direction and velocities of the surface currents as indicated by the drift of icebergs are essentially in agreement with dynamic topographic maps referred to the 1,500 decibar level. In the past

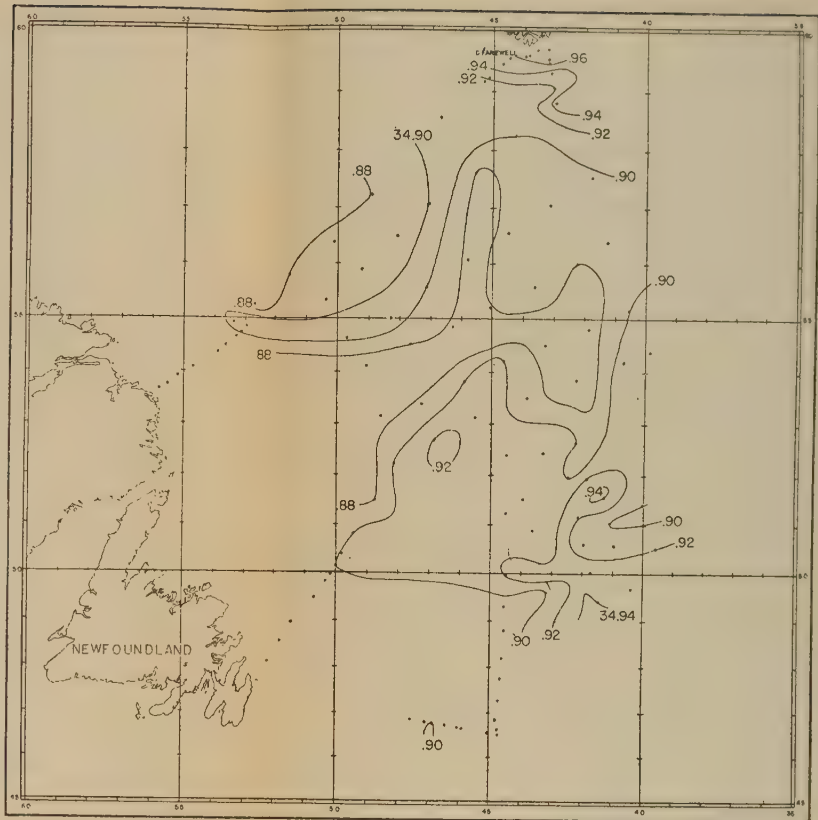
---

[2] The intermediate- deep- and bottom-waters referred to here are those described by Smith, Soule, and Mosby in U. S. Coast Guard Bull. No. 19, Pt. 2; not those of Wüst which differ in thickness, circulation and origin from the above.



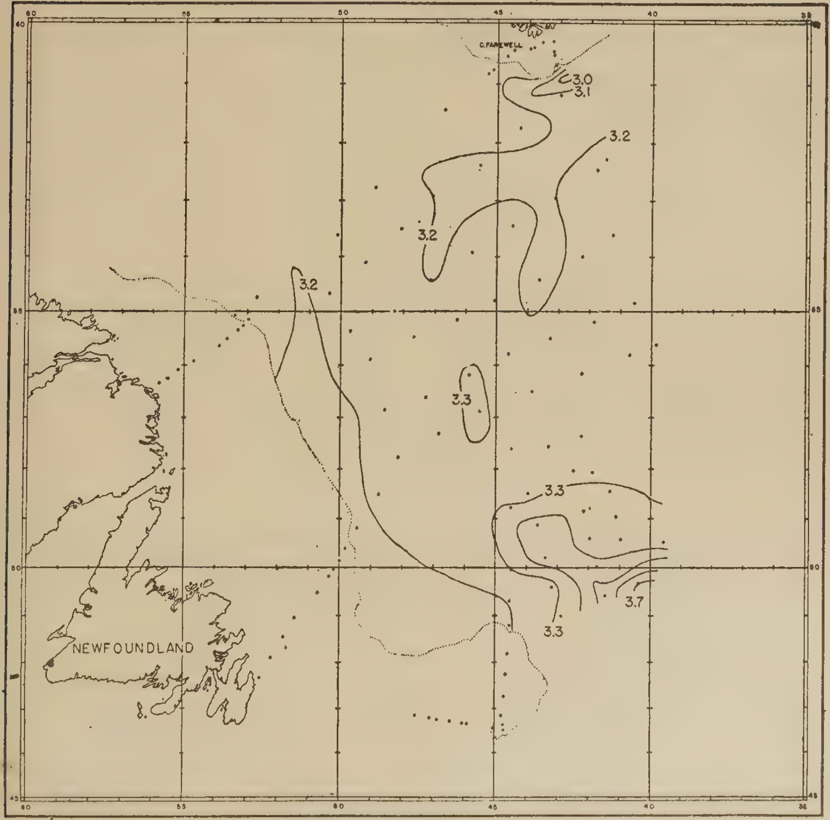
60
55
50
45
40
35
C. FAREWELL
4.5
4.0
4.0
3.8
3.6
3.5
3.4
3.4
3.3
3.3
3.3
3.4
3.3
3.4
3.3
3.4'
3.6
3.2
3.8
4.0
4.2
3.2
3.4
3.6
3.8
4.0
4.2
NEWFOUNDLAND

FIGURE 31.—Temperature at 1,000 meters. July 10–August 23, 1935.



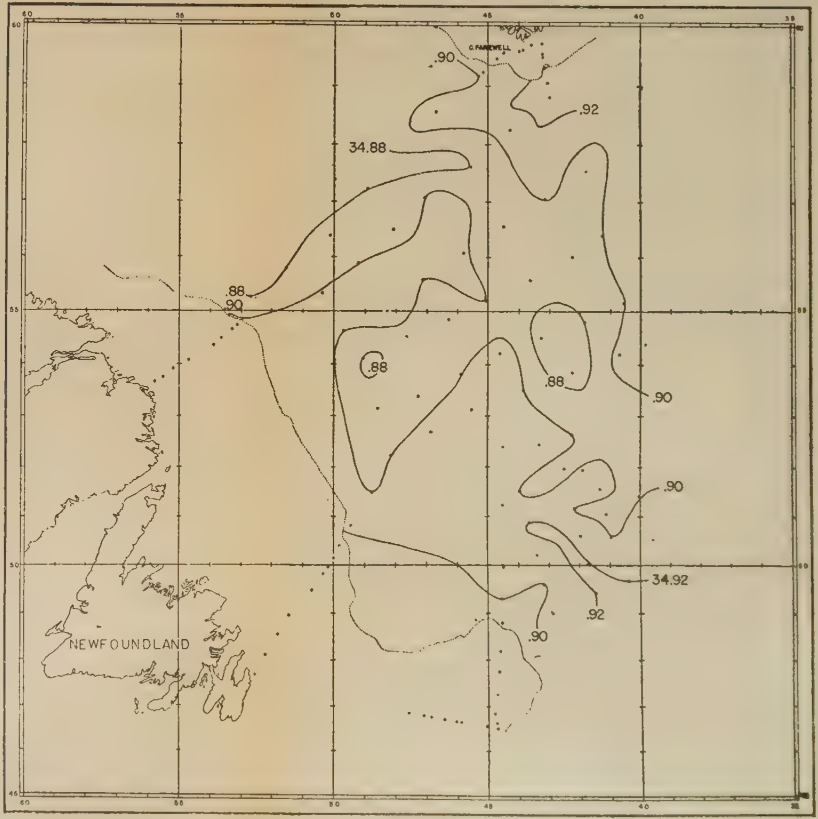
60
55
50
45
40
35
C. FAREWELL
.96
.94
.92
.94
.92
34.90
.90
.88
.90
.88
88
.92
.94
.88
.90
.92
.90
.92
34.94
NEWFOUNDLAND
.90

FIGURE 32.—Salinity at 1,000 meters. July 10–August 23, 1935.



60
55
50
45
40
35
C. FAREWELL
3.0
3.1
3.2
3.2
3.2
3.3
3.3
3.7
3.3
NEWFOUNDLAND

FIGURE 33.—Temperature ot 1,500 meters. July 10–August 23, 1935.



60
55
50
45
40
35
C. FAREWELL
.90
.92
34.88
.88
.90
.88
.88
.90
.90
34.92
.92
.90
NEWFOUNDLAND

FIGURE 34.—Salinity at 1,500 meters. July 10–August 23, 1935.

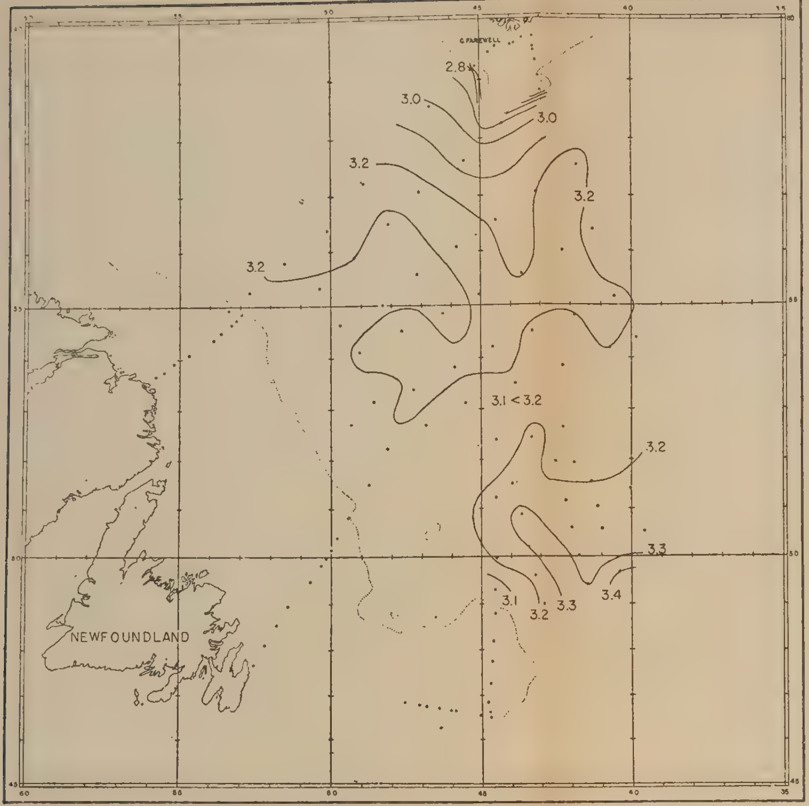

C. FAREWELL
2.8
3.0
3.0
3.2
3.2
3.2
3.1 < 3.2
3.2
3.3
3.1
3.2
3.3
3.4
NEWFOUNDLAND
60
55
50
45
40
35

FIGURE 35.—Temperature at 2,000 meters. July 10–August 23, 1935.

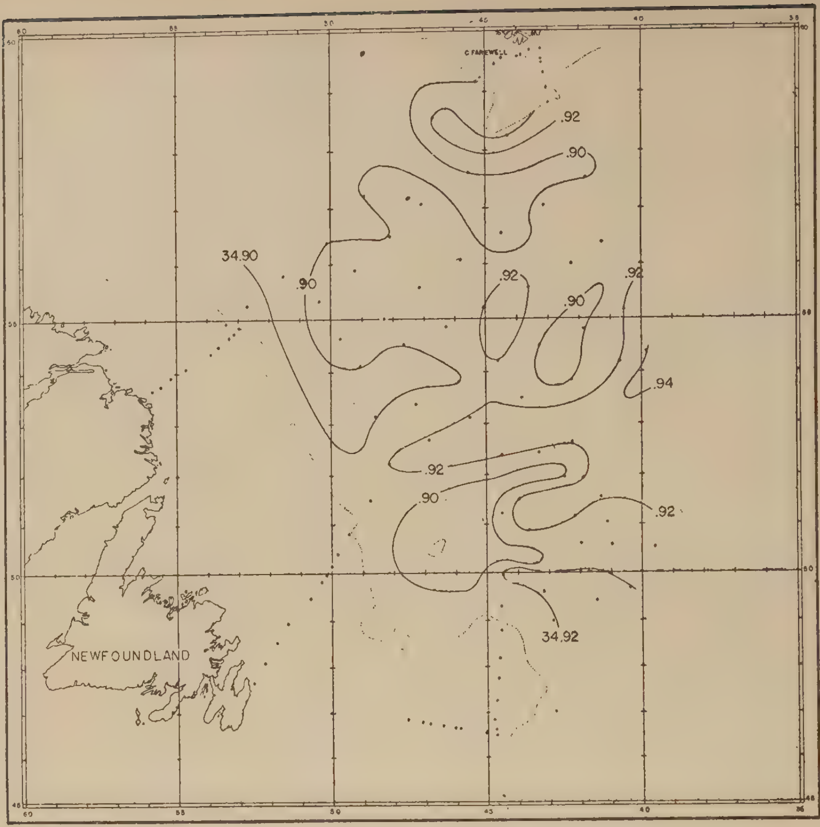

C. FAREWELL
.92
.90
34.90
.90
.92
.90
.92
.94
.92
.90
.92
34.92
NEWFOUNDLAND
60
55
50
45
40
35

FIGURE 36.—Salinity at 2,000 meters. July 10–August 23, 1935.

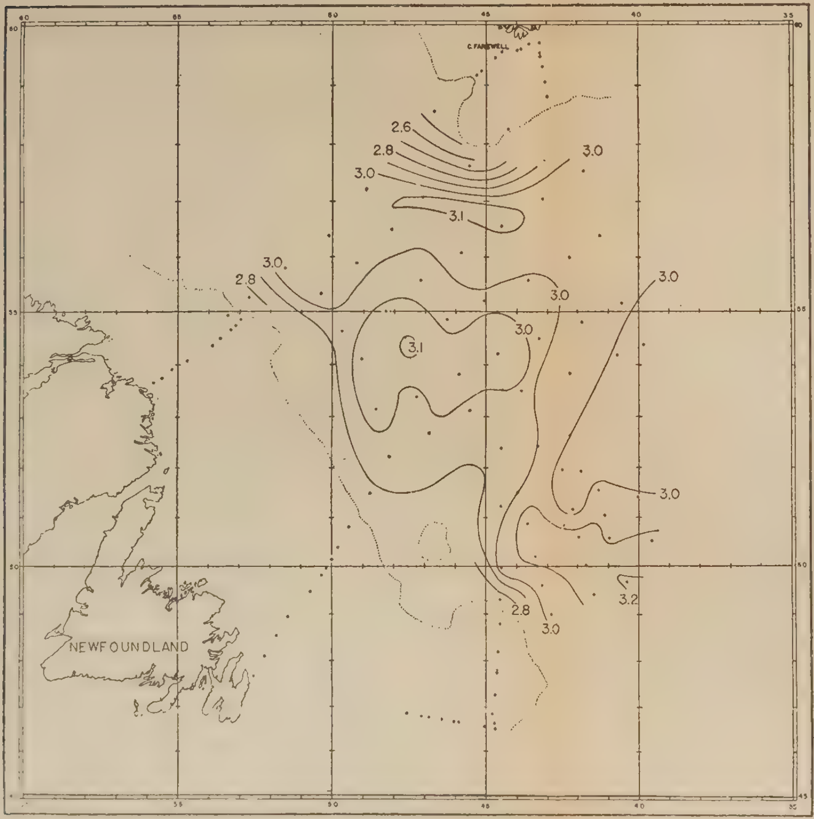

C. FAREWELL
2.6
2.8
3.0
3.0
3.1
3.0
2.8
3.0
3.0
3.1
3.0
3.0
3.0
2.8
3.0
3.2
NEWFOUNDLAND
60
55
50
45
40
35

FIGURE 37.—Temperature at 2,500 meters. July 10–August 23, 1935.

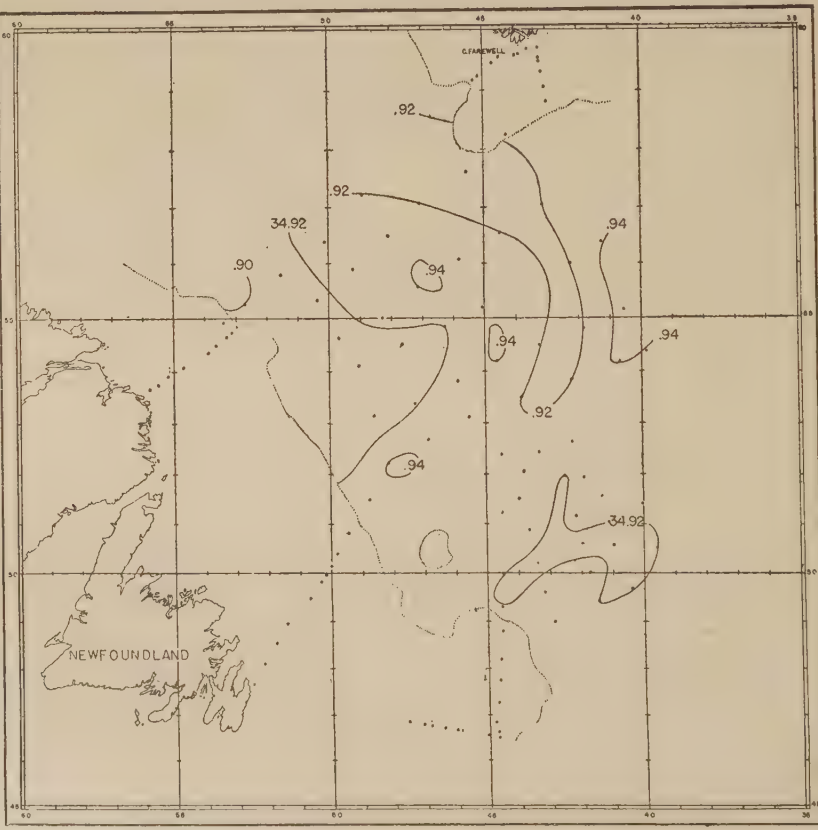

C. FAREWELL
.92
.92
34.92
.90
.94
.94
.94
.94
.92
.94
34.92
NEWFOUNDLAND
60
55
50
45
40
35

FIGURE 38.—Salinity at 2,500 meters. July 10–August 23, 1935.

149346—38 (Face p. 46) No. 2

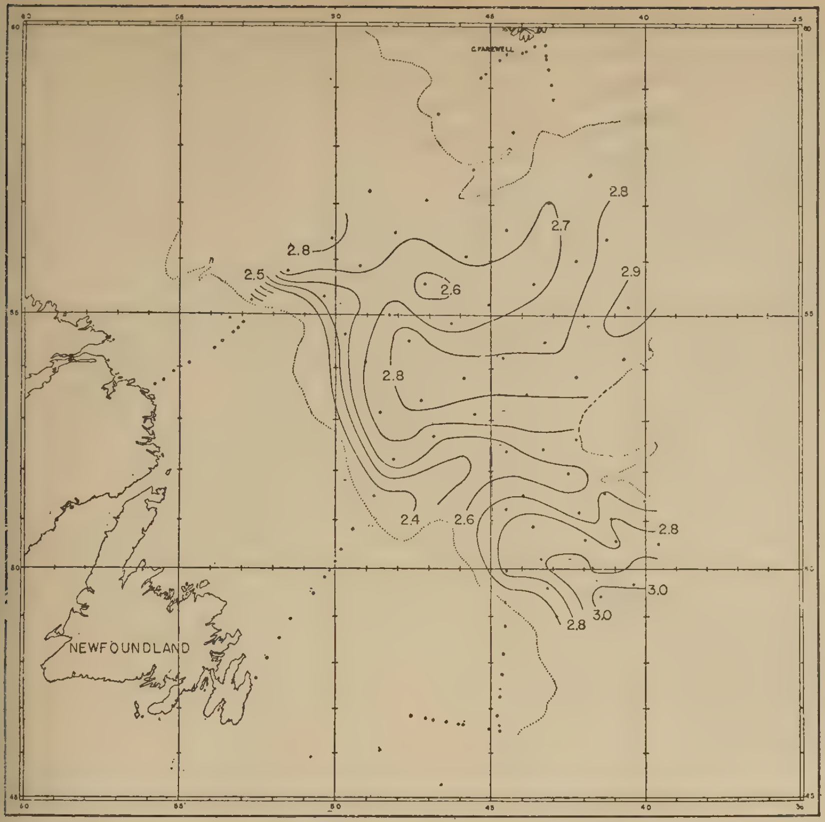

C. FAREWELL
2.8
2.7
2.8
2.5
2.6
2.9
2.8
2.4
2.6
2.8
3.0
3.0
2.8
NEWFOUNDLAND
60
55
50
45
40
35

FIGURE 39.—Temperature at 3,000 meters. July 10–August 23, 1935.

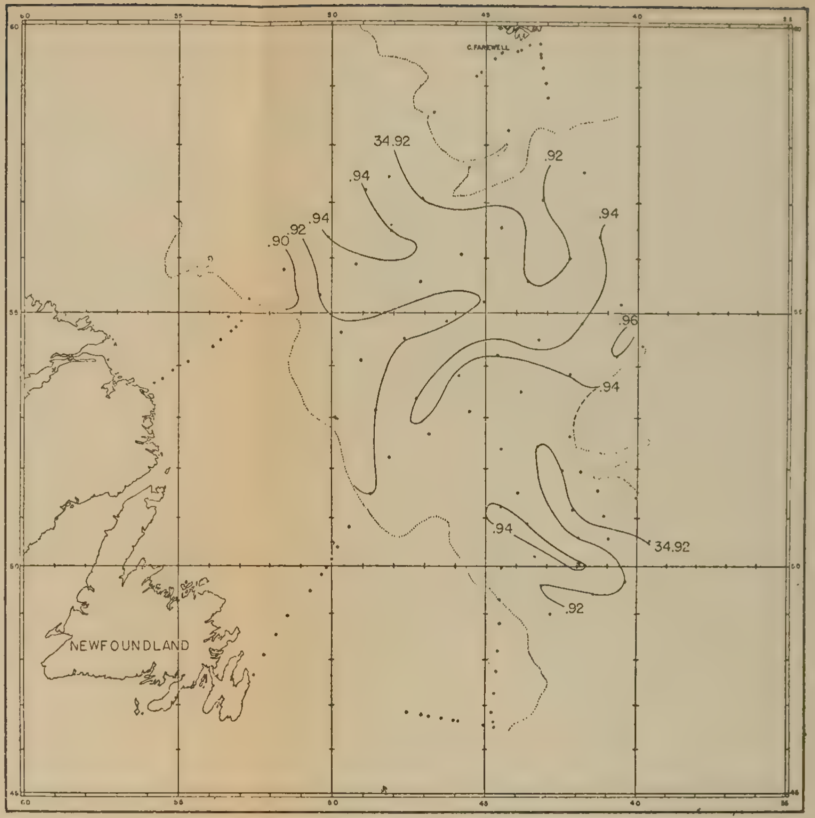

C. FAREWELL
34.92
.92
.94
.94
.92
.90
.94
.96
.94
.94
34.92
.92
NEWFOUNDLAND
60
55
50
45
40
35

FIGURE 40.—Salinity at 3,000 meters. July 10–August 23, 1935.

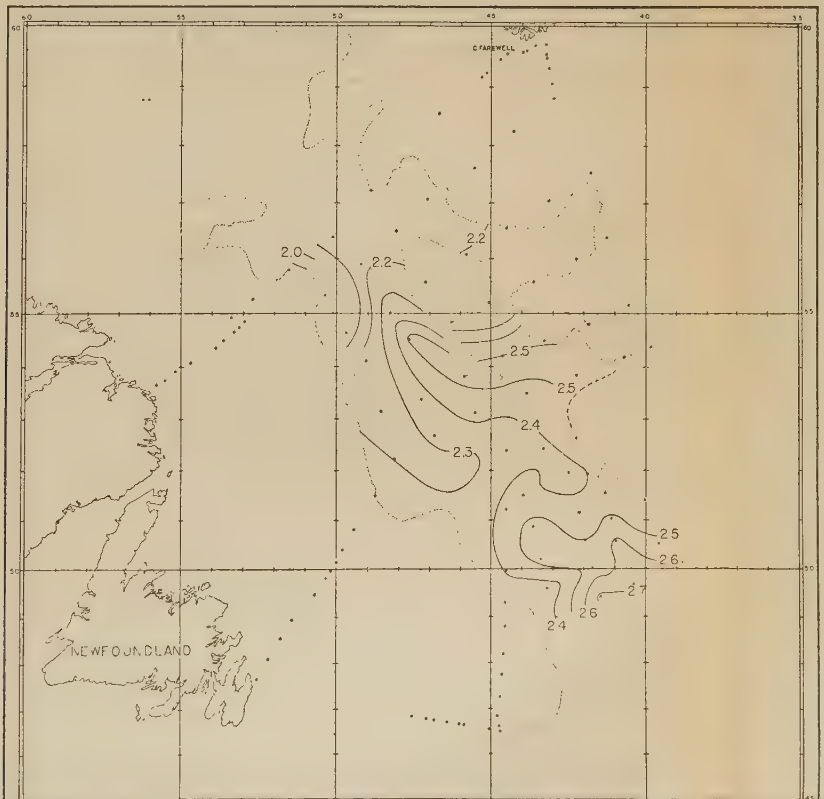

C. FAREWELL
2.0
2.2
2.2
2.5
2.5
2.4
2.3
2.5
2.6
2.7
2.4
2.6
NEWFOUNDLAND
60
55
50
45
40
35

FIGURE 41.—Temperature at 3,500 meters. July 10–August 23, 1935.

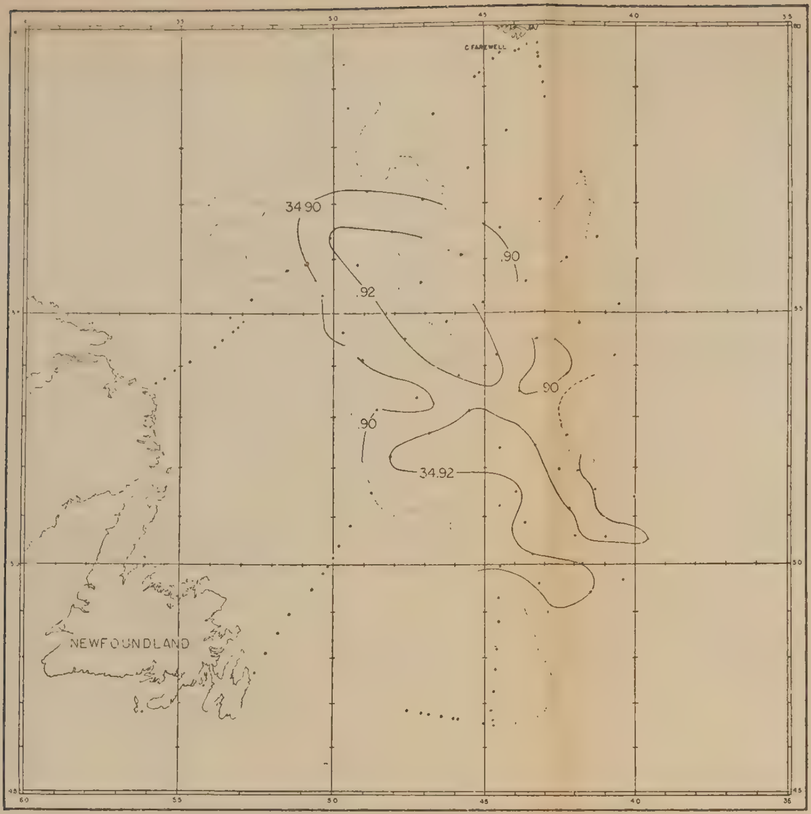

C FAREWELL
34.90
.92
.90
.90
.90
34.92
NEWFOUNDLAND
60
55
50
45
40
35

FIGURE 42.—Salinity at 3,500 meters. July 10–August 23, 1935.

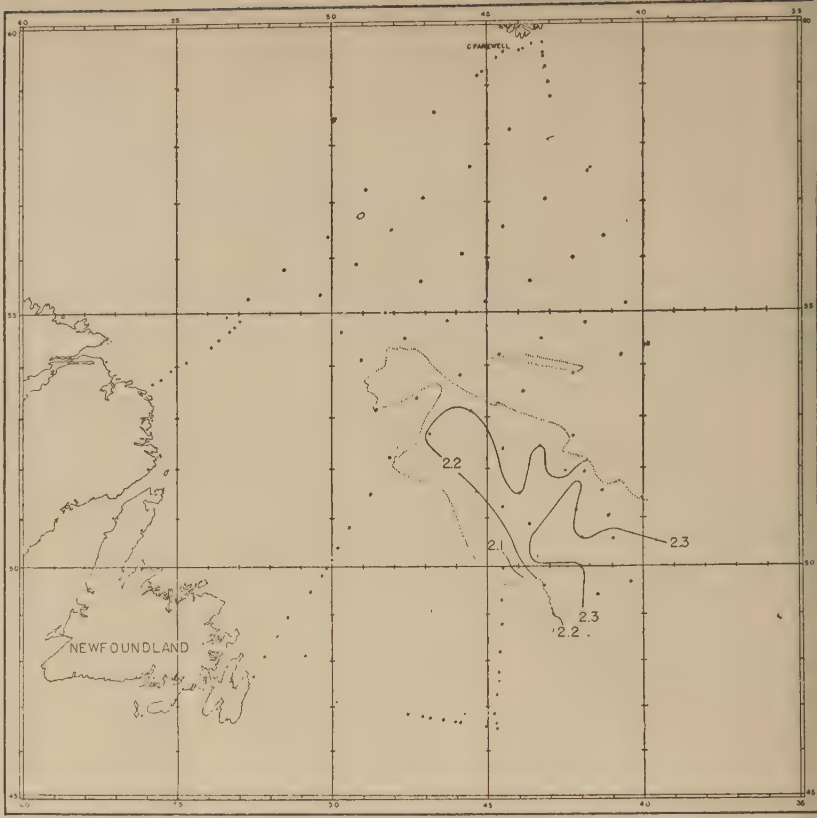

C FAREWELL
2.2
2.1
2.3
2.3
2.2
NEWFOUNDLAND
60
55
50
45
40
35

FIGURE 43.—Temperature at 4,000 meters. July 10–August 23, 1935.

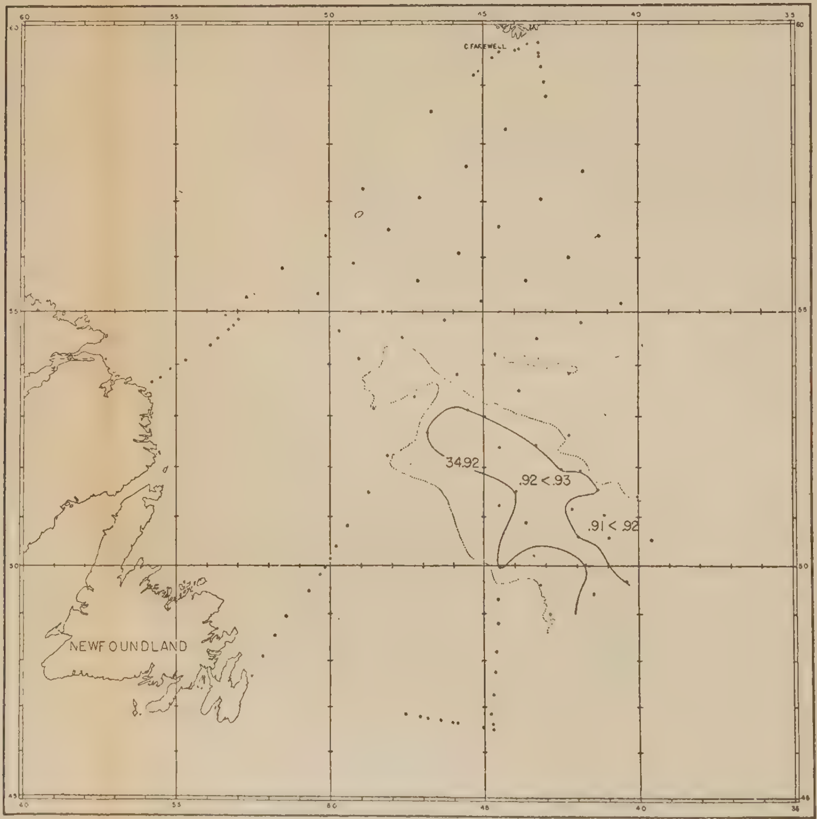

C FAREWELL
34.92
.92 < .93
.91 < .92
NEWFOUNDLAND
60
55
50
45
40
35

FIGURE 44.—Salinity at 4,000 meters. July 10–August 23, 1935.

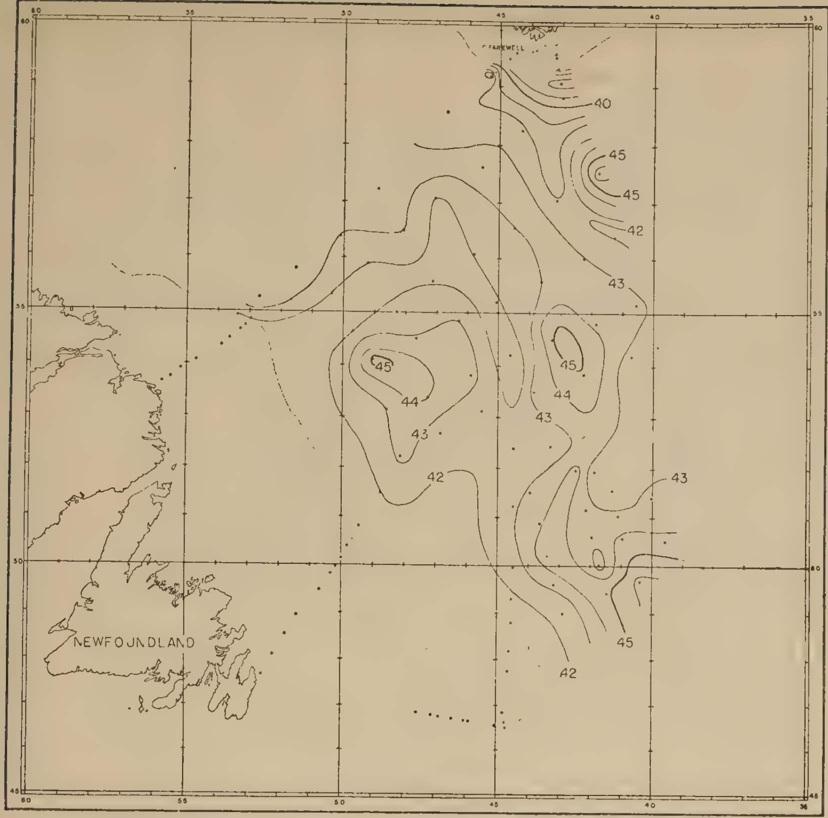

C. FAREWELL
NEWFOUNDLAND
40
45
45
42
43
45
45
44
44
43
43
42
43
45
42
60
55
50
45
40
35

FIGURE 45.—Anomaly of specific volume at 1,500 meters. July 10–August 23, 1935.

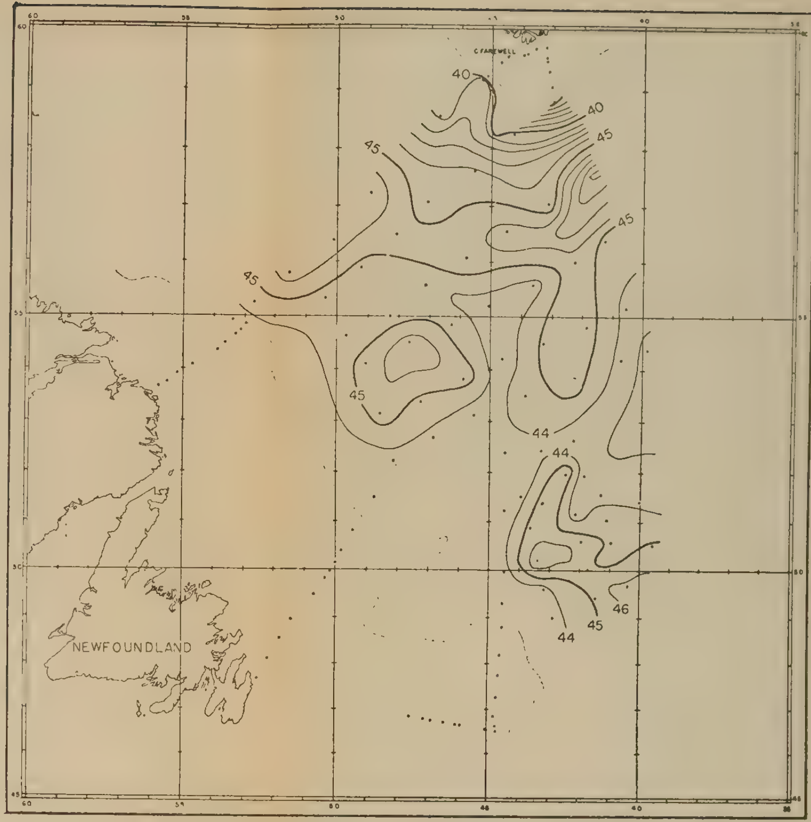

C. FAREWELL
NEWFOUNDLAND
40
40
45
45
45
45
45
44
44
46
45
44
60
55
50
45
40
35

FIGURE 46.—Anomaly of specific volume at 2,000 meters. July 10–August 23, 1935.

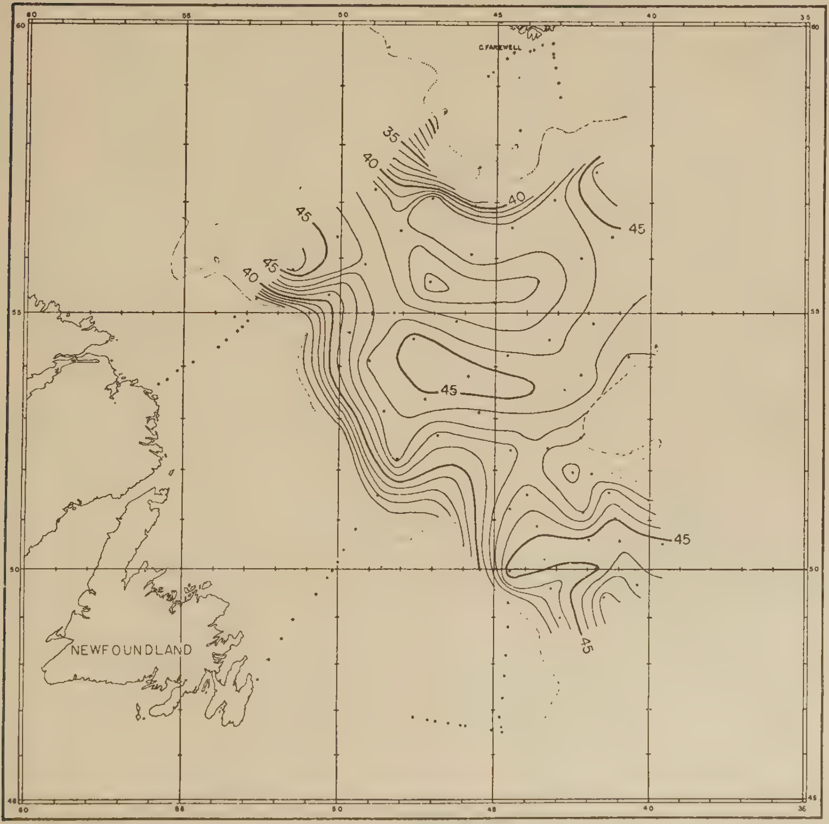

C. FAREWELL
NEWFOUNDLAND
35
40
40
45
45
45
40
45
45
45
60
55
50
45
40
35

FIGURE 47.—Anomaly of specific volume at 3,000 meters. July 10–August 23, 1935.

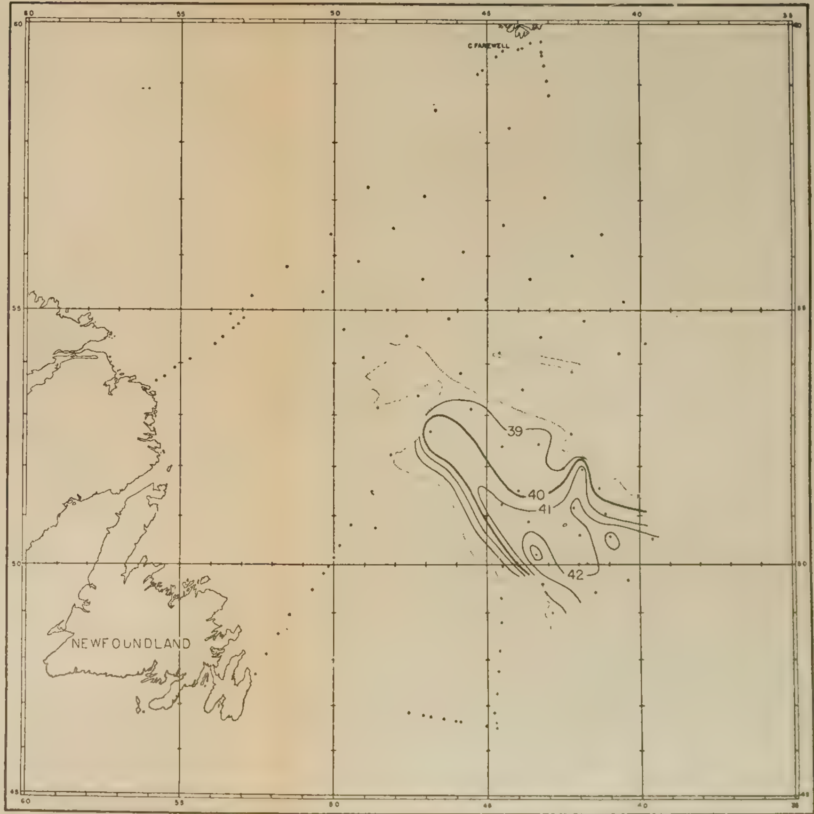

C. FAREWELL
NEWFOUNDLAND
39
40
41
42
60
55
50
45
40
35

FIGURE 48.—Anomaly of specific volume at 4,000 meters. July 10–August 23, 1935.

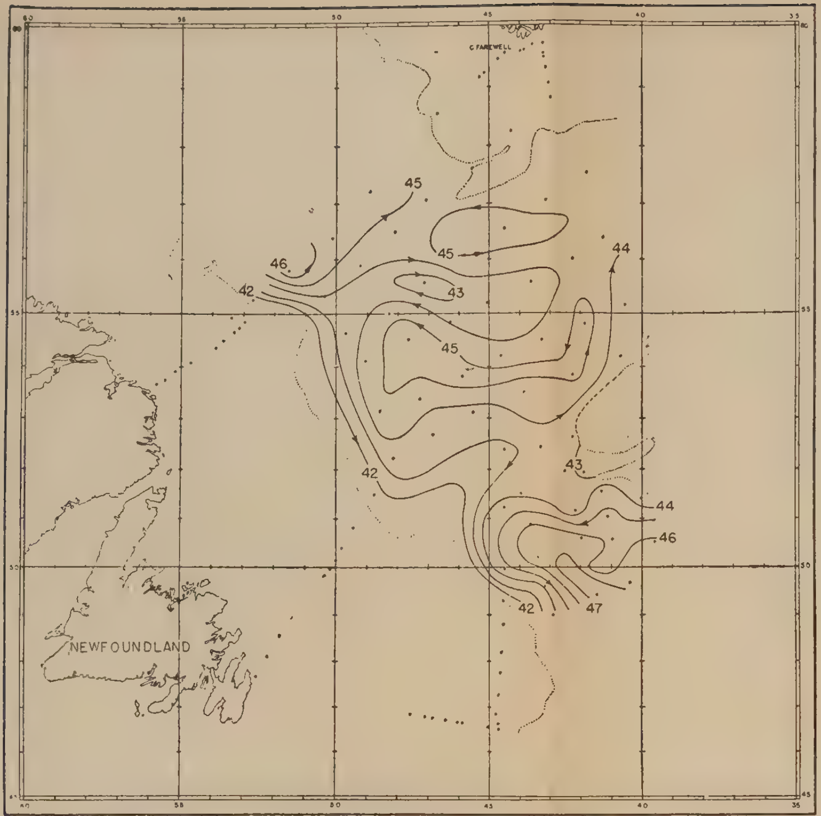

60
55
50
45
40
35
C FAREWELL
45
46
42
45
43
45
44
43
42
44
46
42
47
NEWFOUNDLAND

FIGURE 49.—Dynamic topography at 3,000 decibars relative to 2,000 decibars. July 10–August 23, 1935. Differences in anomaly of dynamic height expressed in centimeters.

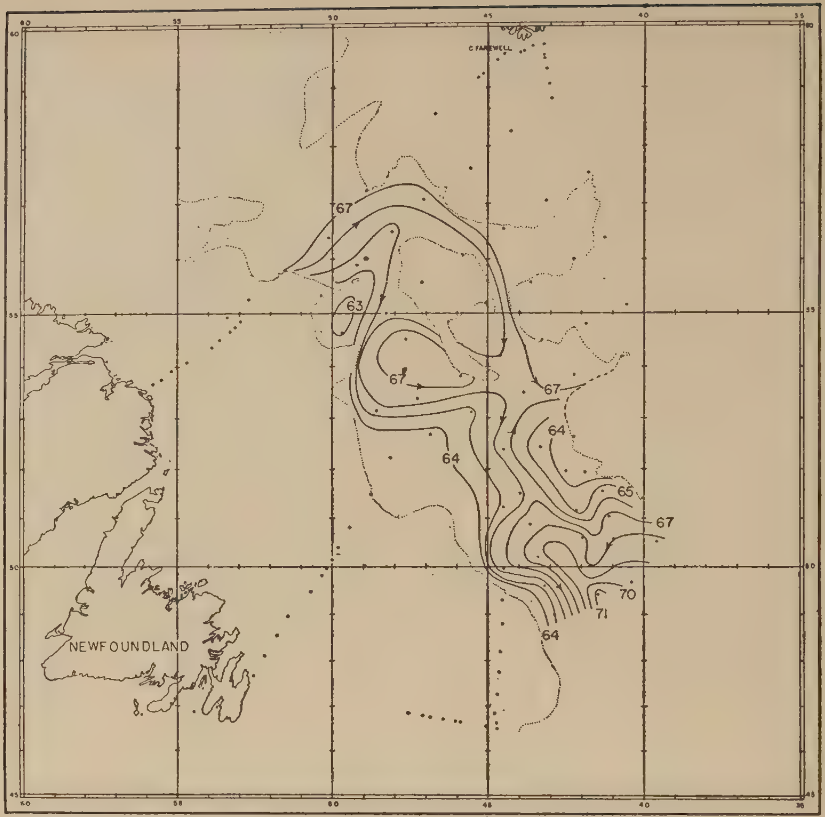

60
55
50
45
40
35
C FAREWELL
67
63
67
67
64
64
65
67
70
71
64
NEWFOUNDLAND

FIGURE 50.—Dynamic topography at 3,500 decibars relative to 2,000 decibars. July 10–August 23 1935. Differences in anomaly of dynamic height expressed in centimeters.

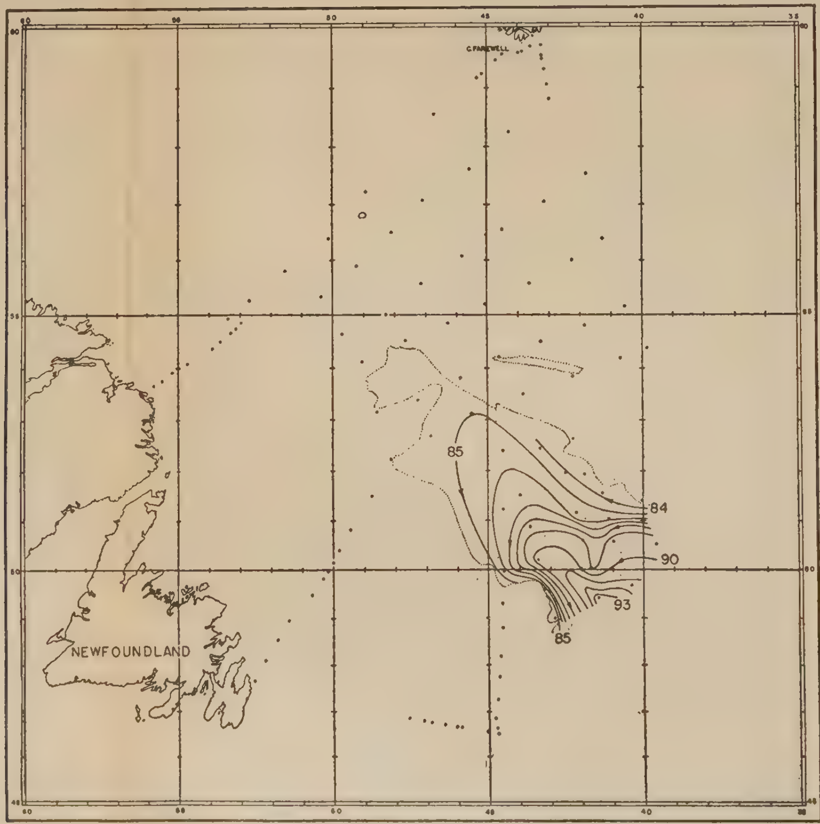

60
55
50
45
40
35
C FAREWELL
85
84
90
93
85
NEWFOUNDLAND

FIGURE 51.—Dynamic topography at 4,000 decibars relative to 2,000 decibars. July 10–August 23, 1935. Differences in anomaly of dynamic height expressed in centimeters.

deeper reference surfaces have not been used for this region chiefly because of the errors which would have been introduced through necessary extrapolations in the many cases where observations did not extend to deeper levels. Since, in this survey, all stations were occupied to as near bottom as was practicable the question arose as to whether the deepest common level would be the best. In order to find the most nearly motionless level in the area as a whole the least variability in vertical differences in dynamic height for any 500-meter layer was selected as a criterion. This investigation showed that the desired level was at about 2,000 meters. This method was checked by inspection of horizontal gradients of anomaly of specific volume. Figures 45 to 48 show the horizontal distribution of anomaly of specific volume for the 1,500, 2,000, 3,000, and 4,000 decibar surfaces and demonstrate that the horizontal gradients are least in the 1,500 and 2,000 decibar surfaces. It will be seen that with the exception of the region immediately south of Cape Farewell, the 2,000 decibar level is indicated as most nearly motionless.

This level was then used as a reference surface in the preparation of the dynamic topographic maps of the 3,000, 3,500, and 4,000 decibar surfaces shown in figures 49 to 51. Admittedly, because of the small density gradients involved and the probably undulatory character of the motionless surface if one exists, the accuracy of these maps is highly questionable as to velocity. It is believed, however, that the indicated directions of flow are reliable in the main. They show the southward movement along the American side of the basin consistent with other criteria of the movement of the deep and bottom waters of the Labrador Sea. They also show that this water is joined by other water from the southern side of the end of Reykjanes Ridge. As to the origin of the latter stream, the absence of observations to the eastward of the area surveyed does not permit of more than a conjecture. The higher temperature points to some source other than the northwestern arm of the Labrador Basin. Possibly, the water in question comes from the northeastern arm of the Labrador Basin to the latitude shown in figures 49–51, by a route eastward of the fortieth meridian. There is even the possibility that it crosses the Mid-Atlantic Ridge from the eastward between latitudes 50° and 55° N. The need for a further survey to determine this question is plainly indicated.

Bottom temperatures.—As previously mentioned, the observations were carried to as near bottom as was practicable at all stations. Thus we have data on which to base good extrapolations to bottom, supported by 20 cases in which the lowest bottle bore evidence of actually having been on bottom. (Such as mud or sand in the lip of the bottle, in the water sample or in the glass case of the unprotected thermometer.) From this material it has been possible to construct reliable charts of the bottom temperature in situ and the potential bottom temperature. These charts are shown in figures 52 and 53, respectively, and apply to depths greater than 1,500 meters. The stations at which actual bottom temperatures were obtained are marked with a cross. The considerable horizontal gradient is in accord with the circulation of the deep and bottom water discussed above and shown in figures 49–51. The lowest temperatures may be looked upon as most characteristic of the bottom water of the Labrador Sea and in this light it is interesting to note that along the American side the axis of minimum temperature follows the channel of greatest depth as the water progresses toward the Newfoundland Basin. In figure 53 the potential temperature has a minimum at about 55° N., 50° W. and another southwestward of Cape Farewell. Considering the seasonal production of the deep water of the Labrador Sea, such minima are to be expected. Furthermore, their temperature and extent may also be expected to vary with the varying severity of the winter of their production. It is doubtful, however, if the location of minima from successive winters can be used for the determination

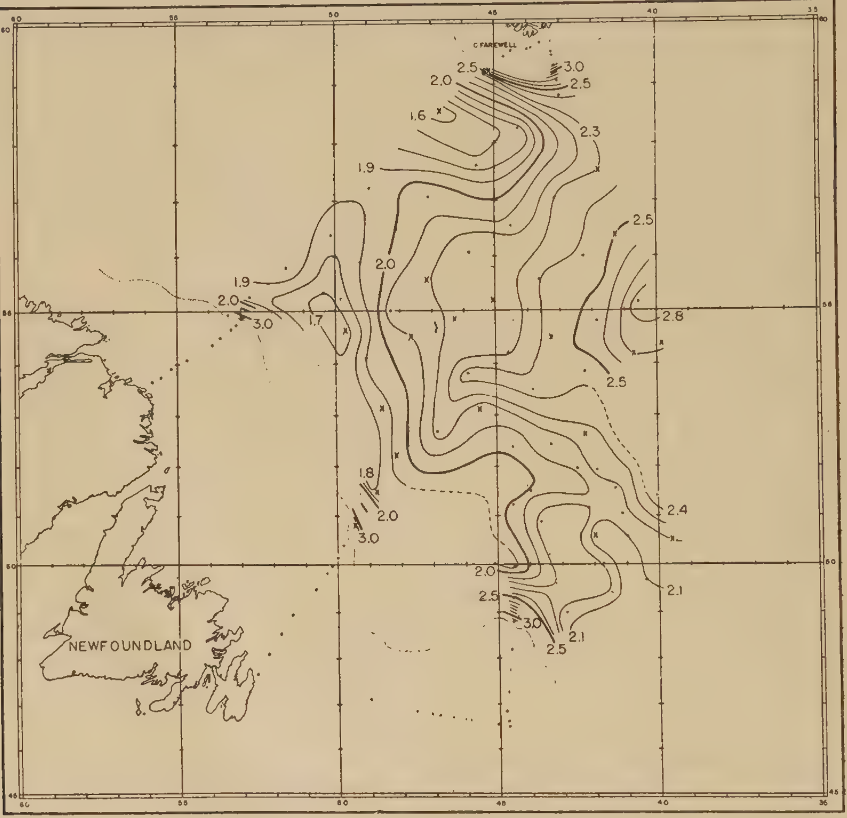
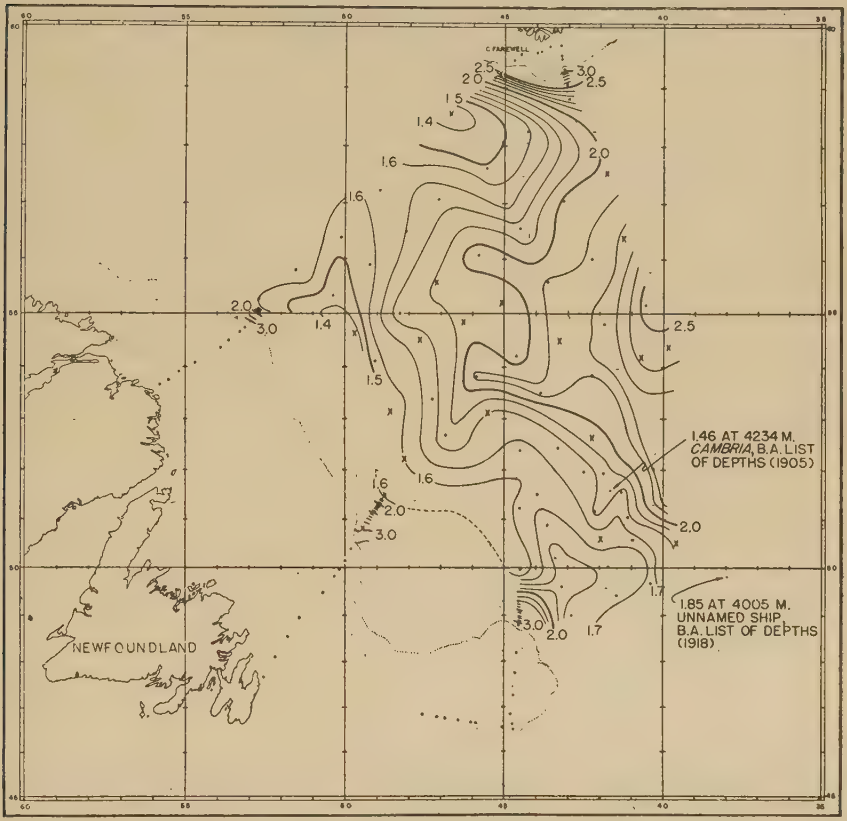


FIGURE 52.—Bottom temperatures in situ for depths greater than 1,500 meters. July 10–August 23, 1935.

of the rate of movement of the deep water because of the possible division of what was originally one into two or more minima, and because of our present ignorance regarding the tortuous path they follow.

For comparison, the two temperatures, upon which Wüst hypothesized the existence of a Newfoundland Ridge, have been plotted on figure 53. The potential temperature of 1.85° C, reported by an unnamed ship in the British Admiralty List of Depths (1918) in latitude 49°49′ N., longitude 38°00′ W., at a depth of 4,005 meters lies somewhat outside the area surveyed but apparently is in good agreement with our observations. The other temperature, 1.46° C., reported by the *Cambria* in the B. A. List of Depths (1905) in latitude 51°34′ N., longitude 41°43.5′ W., at a depth of 4,234 meters, is not in accord with our observations, except as to depth of water. Possibly the observation may have been made during the passage of a temperature minimum produced in an unusually severe winter. One cannot overlook the possibility that if a Fahrenheit thermometer



60
55
50
45
40
35
C FAREWELL
2.5
2.0
3.0
2.5
1.5
1.4
1.6
2.0
1.6
2.0
3.0
1.4
2.5
1.5
1.46 AT 4234 M. *CAMBRIA*, B.A. LIST OF DEPTHS (1905)
1.6
1.6
2.0
3.0
2.0
1.7
1.85 AT 4005 M. UNNAMED SHIP B.A. LIST OF DEPTHS (1918)
3.0
2.0
1.7
NEWFOUNDLAND

Figure 53.—Potential bottom temperatures for depths greater than 1,500 meters. July 10–August 23, 1935.

reading of 35.8° were mistaken for 35.3°, the correct centigrade potential temperature would have been 1.73° which would be much more plausible.

For years the source of the deep water of the North Atlantic has been a much debated topic. The foregoing charts of deep level temperatures (figures 41 and 43), the deep level current maps (figs. 49 to 51), and the bottom temperature charts (figs. 52 and 53), combine to demonstrate the contribution of water from the Labrador Basin to the deep water of the North Atlantic. They further support the picture of the origin and circulation of the waters of the Labrador Sea drawn by Smith, Soule, and Mosby in United States Coast Guard Bulletin No. 19, Part 2.

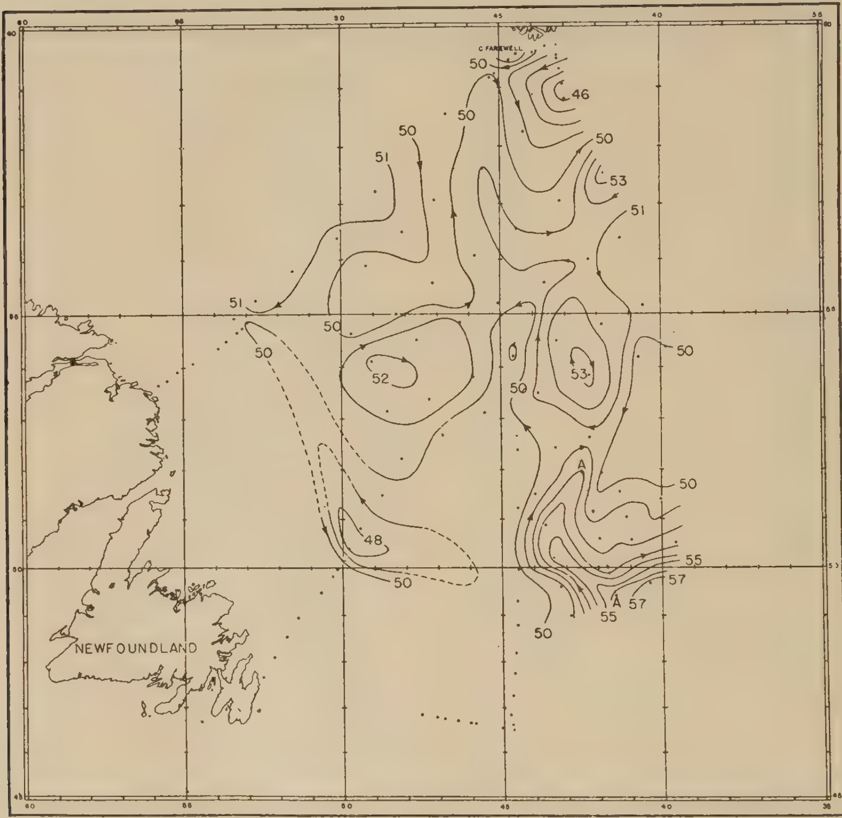


FIGURE 54.—Dynamic topography at 800 decibars relative to 2,000 decibars. July 10–August 23, 1935. Differences in anomaly of dynamic height expressed in centimeters.

Lateral mixing.—As Wüst [3] has considered that in the region covered by this survey we have a source of North Atlantic intermediate water which has a major southward component, it will be of interest to present here figure 54, which is a dynamic current chart showing the horizontal motion at the 800-decibar surface relative to the 2,000-decibar surface. In the manner in which Wüst has shown his intermediate water graphically, it should be moving southward at about this level (800 meters) in the southern part of the area covered by figure 54. However, it is evident from figure 54 that in this region the general movement of the water at 800 meters is in a direction similar to that of the Atlantic Current and has a major northeasterly component. The intermediate water of Wüst is identified by the criterion of minimum salinity and such water has been found, not only by others, but also in this survey and in this particular region. However, as pointed out by Smith, Soule, and Mosby in United States Coast Guard Bulletin No. 19, Part 2, it should be looked upon not as a direct southward sinking from near the surface in the vicinity of the "polar front", but as the product of mixing, cabbeling and gradual sinking taking place along the borders of the Labrador Current, the resulting mixed water following the same general directions as the parent currents. This view does not deny the possibility of lateral transfer by mixing. On the contrary, the very observations which demonstrate, in figure 54, the direction of horizontal motion of this water may help to clarify the mechanism of such lateral transfer. Rossby,[4] in his work on wake streams, and Parr,[5] in his work on the Caribbean, have concluded from independent considerations that horizontal mixing is a maximum where vertical stability is a maximum. This principle can be applied to the low-salinity water in the vicinity of the fiftieth parallel. In figure 55 is shown a vertical section of salinity approximately at right angles to the direction of flow. The geographical location of the section is indicated by the line AA in figure 54. Here we see a tongue of minimum salinity whose axis lies at about 800 meters at the left hand (southern) end of the section and at successively higher levels to the right (north). In figure 56 the vertical stability,[6] expressed as the depth rate of change of σ_t, has been shown for the same section. The axis of maximum stability is shown to approximate with remarkable closeness the axis of minimum salinity shown in figure 55. Above this axis of maximum stability is a layer of minimum stability. At depths of about 2,000 meters and 3,000 meters another minimum and maximum are indicated, but because of the errors involved in determining the stability the reality of such a minimum and maximum is questionable at present.

---

[3] Die Stratosphäre. Wissenschaftliche Ergebnisse der Deutchen Atlantischen Expedition auf dem Forschungs- und Vermessungsschiffe *Meteor*, 1925–27. Band VI. Erster Teil. Berlin. 1935.

---

[4] C. G. Rossby. Dynamics of steady ocean currents in the light of experimental fluid mechanics. Papers in Phys. Oceanog. and Met. M. I. T. and W. H. O. I., vol. V, no. 1. Aug. 1936. Cambridge.

[5] A. E. Parr. A contribution to the hydrography of the Caribbean and Cayman Seas. Bull. Bingham Oceanog. Collection, vol. V, art. 4, 1936. New Haven.

[6] Strict adherence to the definition of stability permits only the determination of the average stability of a layer so that in order to determine the stability at a point one must estimate the course of a smooth curve of vertical distribution drawn with regard to a succession of computed averages for a series of layers. The accuracy of the resulting value of stability at a point will therefore depend on the assumed course of the smooth curve. Such individual values of stability are therefore approximations. Another method for determining good approximations to point-stabilities is to graphically determine tangents to a carefully drawn vertical distribution curve of potential densities ($\sigma_{t\varphi}$). As the potential density, $\sigma_{t\varphi}$, is not significantly different from the corresponding σ_t in depths less than 1,000 meters, and as the phenomena considered occur in these shallow depths, the stabilities made use of here are the graphically determined tangents to vertical distribution curves of σ_t; the use of true stabilities being regarded as an unnecessary refinement.

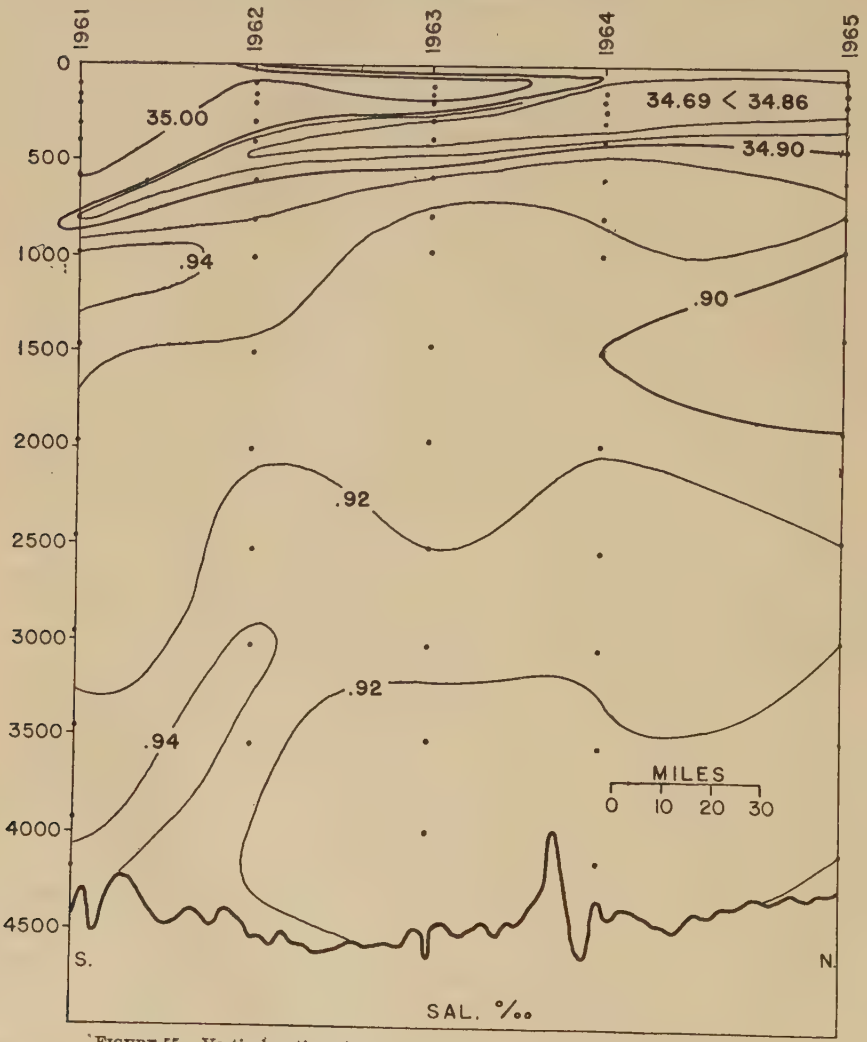


FIGURE 55.—Vertical section of salinity. Stations 1961 to 1965. July 15–17, 1935.

If lateral mixing actually is a maximum at levels of maximum stability the good agreement between the location of the axes of minimum salinity and maximum vertical stability shows that this tongue of low salinity arises from lateral mixing as the mixed water along the border of the Atlantic Current follows the course of that current as indicated by figure 54. It should be emphasized that the topographic dynamic charts, such as figure 54, give the major direction of flow and that lateral mixing, as indicated in the vertical sections, does not involve major velocity components of the water mass.

Similar vertical sections of salinity and vertical stability have been prepared for sections approximately at right angles to the major direction of flow at locations ranging from that of the section shown in figures 55 and 56 to the Tail of the Grand Banks. These sections are shown in figure 57 and their geographical locations are indicated in the inset. Section B of figure 57 is based on observations taken in July 1935, and sections C, D, E, and F are based on observations taken in May 1936. Most of these sections show the same charac-

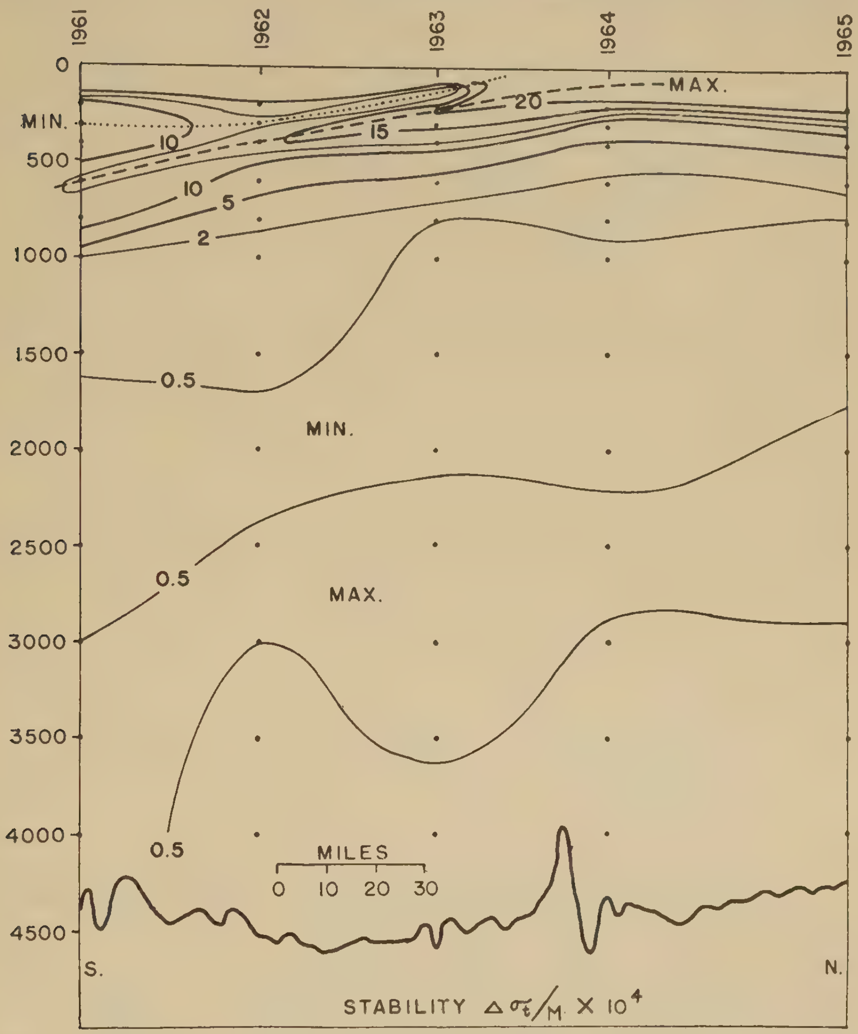
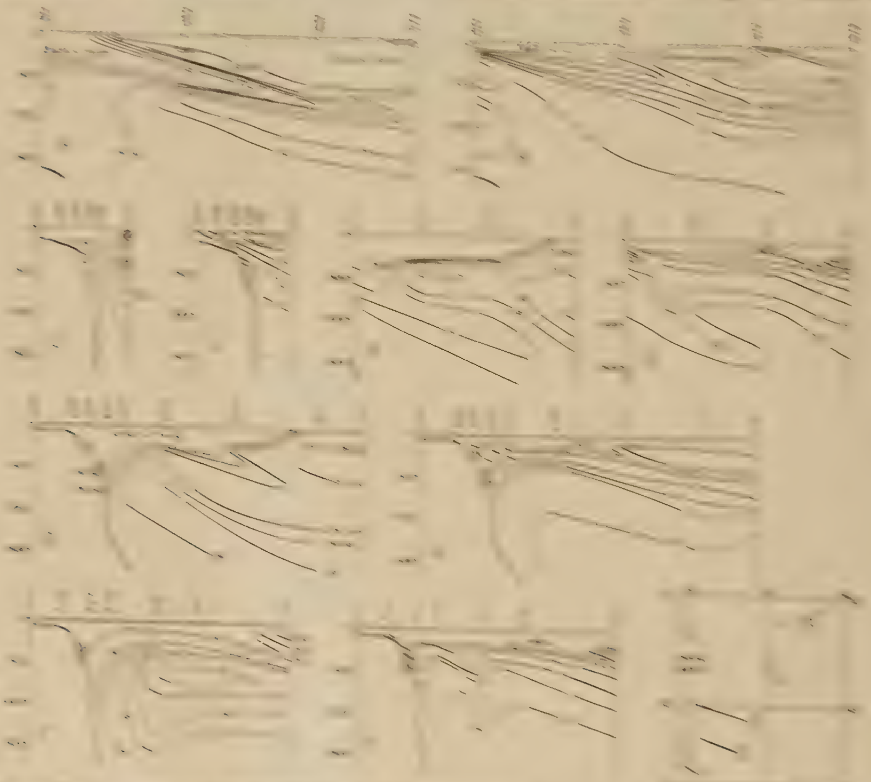


FIGURE 56.—Vertical section of vertical stability, expressed as depth rate of change of σ_t. Stations 1961 to 1965. July 15–17, 1935.

exact correspondence between a salinity minimum and a vertical stability maximum. There is no apparent reason why a lateral mixing along the border between waters of contrasting salinity should be evidenced invariably by the intrusion of a tongue of minimum salinity into the water of higher salinity. This is more often the case in the sections investigated but sections C and D show what may also be regarded as similar evidences of lateral mixing in which a



[illegible]

tongue of maximum salinity intrudes into the water of lower salinity. Section C does not extend far enough toward the Labrador Current to show fully the lateral mixing taking place along this section. Sections D, E, and F intersect not only the margin of the Atlantic Current but the Labrador Current as well. In section D in addition to the vertical stability maximum indicated by the broken line and corresponding to a tongue of maximum salinity extending westward, another less pronounced stability maximum is to be seen over the slope of the Grand Banks which may be related to the [illegible] of the [illegible] [illegible]. This may be interpreted as a correspondence with a salinity minimum. The distortions produced by the [illegible] horizontal and vertical scales should not be lost sight of. In section 2 the left-hand vertical stability maximum is clearly associated with an eastward-trending salinity maximum. The stability maximum toward the surface and on the right-hand side of the section might be considered as corresponding with either an eastward-trending salinity minimum or a westward-trending salinity maximum. The latter consideration is correct in the author's opinion. Section 3 shows an undoubted correspondence between the right-hand stability maximum and a southward-trending salinity minimum. The left-hand stability maximum probably corresponds with the tongue of the [illegible] near the [illegible] similar to the case of section 2. The middle stability maximum is the only one of those investigated which is not apparently related to an intruding tongue of maximum or minimum salinity, and this may be because at this point in section 3 the major direction of flow is nearly parallel to the section and therefore the salinity section cannot portray a lateral intrusion.

The sections shown in figures 15, 16, and 17 indicate that along the borders of the Labrador Current and Atlantic Current, where these borders are abrupt, lateral mixing taking place at levels where the vertical stability is a maximum, is characterized by an intrusion of water from the parent current into the adjacent border water. Where the border transition is not so abrupt, and where the border water is present in considerable volume, the lateral mixing is characterized by intrusion of border water toward the parent current. Although further investigation will be necessary before it is known how far the above conclusions can be accepted as generalities, the implications are that we have here a possible mechanism for transferring across major ocean currents not only physical characteristics but nutrient salts and plankton, flora and fauna having no inherent power of locomotion. (See also A. C. Redfield, Science, vol. [illegible], p. [illegible], Jan. 12, [illegible].)

Attention is called to the fact that in all of the sections investigated the core of maximum lateral mixing, as indicated by the cores of maximum or minimum salinity, are slightly below the corresponding zone of maximum vertical stability. It is as if the zone of maximum vertical stability acted as a protecting layer from disturbances from above and thus permitted lateral mixing to reach a maximum immediately below it.

1936 POST SEASON CRUISE

As has been mentioned, the post-season cruise in 1936 consisted of a complete section from South Wolf Island, Labrador, to Cape Farewell, Greenland, and a shorter section running in to the mouth of Arsuk Fjord outside of Ivigtut, Greenland. The South Wolf Island–Cape Farewell section has been occupied previously in 1928 and 1931 and approximately in 1933, 1934, and 1935. It is considered that the general features of the distribution of temperature and salinity in this section are sufficiently well known from earlier reports (particularly U. S. Coast Guard Bull. No. 19, Pt. 2) that the 1936 conditions need not be shown graphically here for the entire section. The intermediate water was somewhat warmer and saltier than usual with no intermediate temperature minimum present. Both of these departures from normal may be results of the recorded excessive volume of flow of the West Greenland Current in 1935. As the West Greenland Current is the source of the warm and salty constituent of the mixture forming the intermediate water of the Labrador Sea, a primary result of an increase of this current would be the abnormal temperatures and salinities noted above.

Regarding the absence of a temperature minimum in the intermediate water in the South Wolf Island-Cape Farewell section, it is to be expected that under conditions of abnormally large volume of flow of the bordering currents a smaller central area would be subjected to wintertime vertical convection even with normal winter weather conditions. The increase in northward heat transport accompanying the 1935 flood of the West Greenland Current might also be expected to further reduce the amount of wintertime vertical convection through the mitigation of the severity of the winter weather. Thus the flooding of the West Greenland Current is looked upon as producing the earlier erasure of the intermediate temperature minimum which has been regarded as the last cyclic remnant of the wintertime conditions hypothesized by Smith, Soule, and Mosby in Bulletin No. 19, Part 2.

The cold inshore band of the Labrador Current was more extensive than in 1935 and the inshore portion of the West Greenland Current was colder than in 1935. However, the difference in the season (June 20–23, 1936, compared with Aug. 19–23, 1935) probably accounts for these discrepancies. The Irminger Current constituent of the West Greenland Current was more extensive in cross section than in 1935 but the maximum salinity was normal, being 35.06‰.

On this section at station 2254, which was located just inshore of the core of Irminger-Atlantic water, the observations show a case of such marked instability as to merit special consideration. The inshore portion of the section is shown in figure 58. Superimposed on the section showing the distribution of σ_t are the 4° and 5° isotherms and the 34.95 and 35.00‰ isohalines to indicate the location of the Irminger-Atlantic water. From the smooth shape of the isotherms there is no cause to suspect the temperatures. The salinities were noted to be abnormal and the samples were titrated the following day. The titration gave values 0.02 and 0.03‰ even higher salinity than the original conductivity measurements. As no other salinities at this station were as high, one cannot attribute the results to an inter-change of sample bottles. The presence of a valley in the bottom at about this level between stations 2254 and 2255 suggests the possibility of a restricted flow during which the T–S relationship of Irminger-Atlantic water was modified through melting of berg ice but quantitative consideration shows that this would affect the temperature by only about ¼° whereas about 10 times that amount of change would

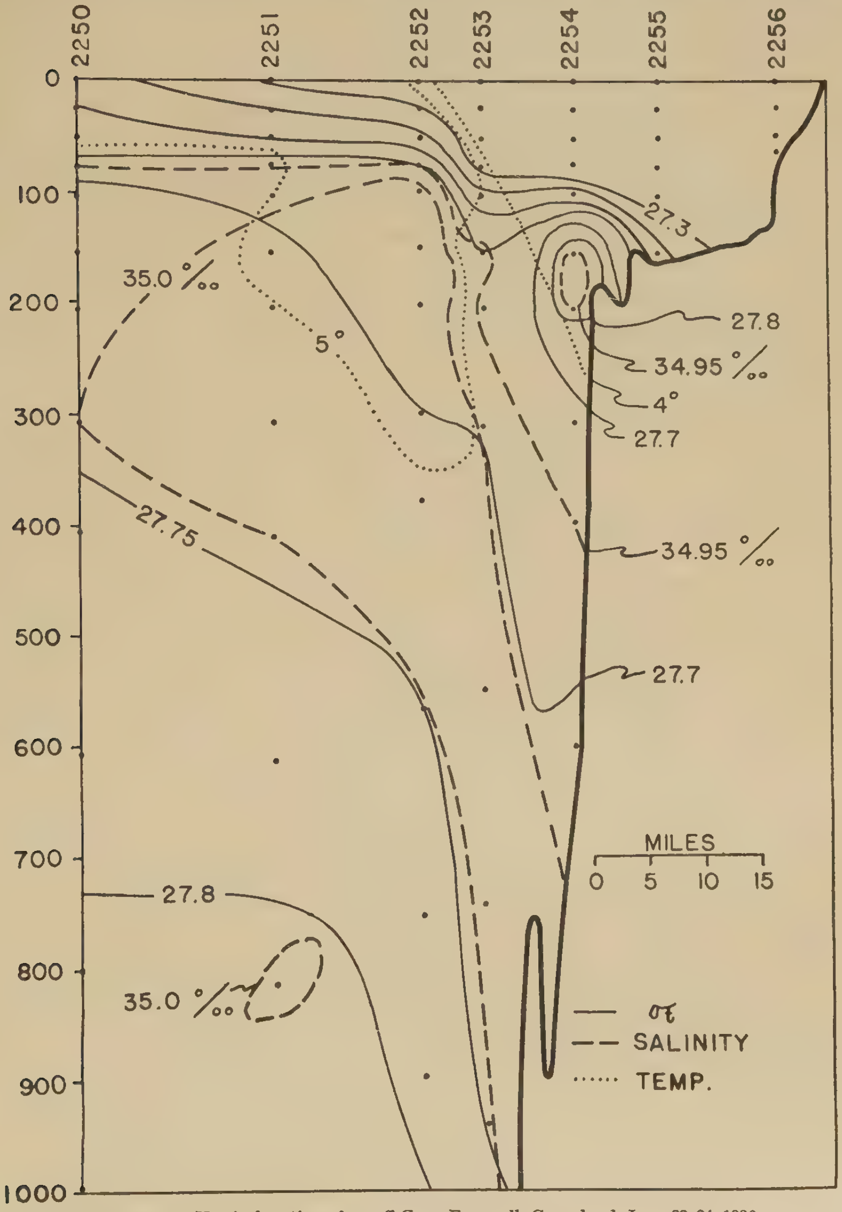


FIGURE 58.—Vertical section of σ_t, off Cape Farewell, Greenland, June 23–24, 1936.

be required to convert water of the characteristics of the core of the Irminger-Atlantic water to the condition found at 150–200 meters at station 2254. The observations seem to be in error but attention is called to them because no definite reason for discarding them can be found.

The Labrador Current at South Wolf Island had a volume of flow of 3.3 million cubic meters per second and a mean temperature of 1.27° C. These figures may be compared with average values of 4.46 and 2.38, respectively, for the years 1928, 1931, 1933, 1934, 1935, and 1936. At Cape Farewell the West Greenland Current had a volume of flow of 6.4 million cubic meters per second and a mean temperature of 4.05° C. with a resulting northward heat transfer of 25.8 million cubic meter degrees centigrade per second. The averages for eight occupations of this section are respectively 5.3, 4.6, and 24.4 expressed in similar units.

The Ivigtut section off Arsuk Fjord, Greenland, has been occupied less frequently than has the Cape Farewell section. Up until the 1936 post-season cruise the Ivigtut section had been occupied twice in 1928, once in 1931, and once in 1933. During two of these three years the volume of flow of the West Greenland Current off Ivigtut was found to be greater than the volume of flow off Cape Farewell. Consequently there was some doubt as to whether or not the volume of flow passing the Cape Farewell section was a reliable indicator of the West Greenland Current. Therefore both sections were occupied in 1936 and but little difference was found between the two sections. At Cape Farewell the volume of flow was 6.4 million cubic meters per second compared with 6.0 at Ivigtut, and the mean temperature at Cape Farewell was 4.05° C. compared with 4.0° C. at Ivigtut. The resulting northward heat transfer was hence 25.8 million cubic meter degrees centigrade per second compared with 23.8 at Ivigtut. In the light of these results the writer is inclined toward the belief that these sections give equally reliable criteria for judging the characteristics of the West Greenland Current.

In the following table are given the data collected during the 1936 season and post-season cruises. The individual station headings give the station number, date, geographical position, depth of water, and the dynamic height of the sea surface above the reference surface used in the construction of the dynamic topographic charts shown in figures 25–28. For stations 2048 to 2234 the sea surface is referred to the 1,000-decibar surface and the depth of water is the uncorrected fathometer sounding based on a sounding velocity of approximately 1,483 meters per second. For stations 2235 to 2264, inclusive, the sea surface is referred to the 1,500-decibar surface and the depth of water is the sonic sounding corrected for sounding velocity but not for draft (2 meters) nor for slope. Where the depths of scaled values are enclosed in parentheses, the data are based on extrapolated vertical distribution curves of temperature and salinity. Asterisks appearing before observed temperatures indicate that these temperatures were determined from the depth of reversal and the corrected reading of an unprotected thermometer. The symbol σ_t signifies 1,000 (density −1).

Table of Oceanographic Data

STATIONS OCCUPIED IN 1936

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
Station 2048; Apr. 9; latitude 47°00′ N., longitude 48°44′ W.; depth 91 meters; dynamic height 971.034 meters						
0	0.70	33.30	0	0.70	33.30	26.72
25	.69	33.30	25	.69	33.30	26.72
49	.68	33.30	50	.70	33.30	26.72
74	.60	33.32	75	.60	33.32	26.74
Station 2049; Apr. 9; latitude 46°59′ N., longitude 48°18′ W.; depth 110 meters; dynamic height 971.041 meters.						
0	0.64	33.14	0	0.64	33.13	26.59
21	.64	33.13	25	.65	33.13	26.59
46	.63	33.13	50	.60	33.13	26.59
72	.41	33.30	75	.40	33.31	26.75
98	−.04	33.48	100	−.10	33.53	26.95
Station 2050; Apr. 9; latitude 46°57′ N., longitude 47°40′ W.; depth 169 meters; dynamic height 971.058 meters.						
0	−0.72	32.72	0	−0.72	32.72	26.32
24	−.70	32.74	25	−.70	32.74	26.34
48	−.66	32.83	50	−.65	32.85	26.42
73	−.44	33.20	75	−.45	33.22	26.71
97	−.27	33.40	100	−.25	33.42	26.87
145	.20	33.61	150	.25	33.62	27.01
Station 2051; Apr. 9–10; latitude 46°55′ N., longitude 47°04′ W.; depth 714 meters; dynamic height 970.954 meters.						
0	−.77	32.82	0	−0.77	32.82	26.40
23	−.76	32.84	25	−.75	32.84	26.42
46	−.76	32.87	50	−.75	32.90	26.47
69	−.59	33.18	75	−.50	33.28	26.76
92	−.40	33.57	100	−.35	33.63	27.04
138	------	33.92	150	−.10	34.00	27.32
255	2.67	34.58	200	1.60	34.31	27.47
426	3.93	34.94	300	3.20	34.73	27.68
			400	3.85	34.92	27.76
			(600)	3.85	34.95	27.78
Station 2052; Apr. 10; latitude 46°55′ N., longitude 46°59′ W.; depth 1,106 meters; dynamic height 970.912 meters.						
0	−0.25	33.13	0	−0.25	33.13	26.63
24	−.17	33.16	25	−.15	33.16	26.66
47	−.05	33.20	50	−.05	33.21	26.69
71	.40	33.60	75	.55	33.68	27.04
94	1.43	34.05	100	1.50	34.10	27.31
141	1.95	34.33	150	2.05	34.38	27.50
188	2.60	34.56	200	2.75	34.60	27.61
282	3.39	34.78	300	3.50	34.80	27.70
572	3.97	34.95	400	3.80	34.89	27.74
771	3.77	34.95	600	3.95	34.95	27.77
971	3.55	34.95	800	3.70	34.95	27.80
			(1,000)	3.50	34.95	27.82

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
Station 2053; Apr. 10; latitude 46°53′ N., longitude 46°28′ W.; depth 622 meters; dynamic height 970.812 meters.						
0	4.32	34.36	0	4.32	34.36	27.27
26	4.32	34.36	25	4.30	34.36	27.27
53	4.32	34.36	50	4.30	34.36	27.27
79	3.90	34.68	75	3.95	34.68	27.56
106	3.80	34.73	100	3.80	34.72	27.61
159	4.22	34.87	150	4.20	34.85	27.67
211	4.02	34.89	200	4.05	34.88	27.71
317	3.95	34.96	300	3.95	34.95	27.77
388	4.08	34.98	400	4.10	34.98	27.79
581	3.58	34.95	600	3.55	34.94	27.80
Station 2054; Apr. 10; latitude 46°52′ N., longitude 46°08′ W.; depth 320 meters; dynamic height 970.810 meters.						
0	4.50	34.41	0	4.50	34.41	27.29
25	4.48	34.41	25	4.48	34.41	27.29
51	4.47	34.41	50	4.45	34.41	27.29
76	4.30	34.52	75	4.30	34.51	27.39
102	3.93	34.66	100	3.95	34.64	27.52
153	4.18	34.86	150	4.15	34.84	27.66
204	4.07	34.94	200	4.10	34.94	27.75
306	3.63	34.94	300	3.65	34.94	27.79
Station 2055; Apr. 10; latitude 46°51′ N., longitude 45°10′ W.; depth 214 meters; dynamic height 970.817 meters						
0	4.85	34.50	0	4.85	34.50	27.32
24	4.76	34.50	25	4.75	34.50	27.33
49	4.74	34.49	50	4.75	34.50	27.33
73	4.72	34.50	75	4.70	34.50	27.33
97	4.14	34.63	100	4.10	34.64	27.51
146	3.81	34.72	150	3.80	34.73	27.62
194	3.78	34.78	200	3.75	34.78	27.66
Station 2056; Apr. 10; latitude 46°52′ N., longitude 45°00′ W.; depth 159 meters; dynamic height 970.819 meters						
0	4.56	34.46	0	4.56	34.46	27.32
27	4.48	34.46	25	4.50	34.46	27.33
54	4.42	34.46	50	4.45	34.46	27.33
81	4.26	34.50	75	4.30	34.47	27.36
108	3.90	34.62	100	3.95	34.59	27.48
156	3.85	34.79	150	3.85	34.69	27.57
Station 2057; Apr. 10; latitude 46°52′ N., longitude 44°41′ W.; depth 139 meters; dynamic height 970.830 meters						
0	4.51	34.44	0	4.51	34.44	27.31
25	4.43	34.44	25	4.43	34.44	27.31
50	4.41	34.44	50	4.41	34.44	27.32
76	4.41	34.45	75	4.40	34.45	27.33
101	3.95	34.60	100	3.95	34.60	27.49
126	3.89	34.64				

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1936—Continued

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σt
Station 2058; Apr. 10; latitude 46°46.5′ N., longitude 44°39′ W.; depth 169 meters; dynamic height 970.845 meters						
0	4.53	34.44	0	4.53	34.44	27.30
26	4.53	34.42	25	4.53	34.44	27.30
53	4.46	34.43	50	4.45	34.44	27.31
79	4.42	34.44	75	4.45	34.44	27.31
106	4.14	34.51	100	4.20	34.48	27.38
159	3.87	34.71	150	3.90	34.69	27.57
Station 2059; Apr. 10–11; latitude 46°38′ N., longitude 44°39′ W.; depth 219 meters; dynamic height 970.829 meters						
0	4.50	34.45	0	4.50	34.45	27.32
26	4.42	34.45	25	4.45	34.45	27.32
53	4.40	34.45	50	4.40	34.45	27.33
79	4.10	34.60	75	4.15	34.58	27.46
105	3.86	34.68	100	3.90	34.67	27.56
158	3.78	34.78	150	3.80	34.77	27.65
211	3.72	34.84	200	3.75	34.83	27.70
Station 2060; Apr. 11; latitude 46°28′ N., longitude 44°40′ W.; depth 631 meters; dynamic height 970.842 meters						
0	4.51	34.51	0	4.51	34.51	27.37
26	4.48	34.50	25	4.50	34.51	27.37
52	4.42	34.52	50	4.45	34.52	27.38
79	4.42	34.52	75	4.40	34.52	27.39
105	4.35	34.55	100	4.35	34.54	27.40
157	3.70	34.70	150	3.70	34.69	27.59
210	3.76	34.78	200	3.75	34.77	27.65
315	3.85	31.90	300	3.85	34.89	27.73
413	3.85	34.94	400	3.85	34.94	27.77
620	3.74	34.95	600	3.75	34.95	27.79
Station 2061; Apr. 11; latitude 46°23′ N., longitude 44°40′ W.; depth 1,829 meters; dynamic height 970.844 meters						
0	5.03	34.60	0	5.03	34.60	27.37
25	5.04	34.60	25	5.04	34.60	27.37
50	5.04	34.60	50	5.04	34.60	27.37
74	5.08	34.61	75	5.05	34.61	27.38
99	5.36	34.71	100	5.35	34.71	27.43
149	5.96	34.96	150	5.95	34.96	27.55
199	4.29	34.78	200	4.25	34.78	27.61
298	3.76	34.84	300	3.75	34.84	27.70
295	3.79	34.84	400	3.80	34.93	27.78
449	3.84	34.95	600	3.75	34.96	27.80
606	3.74	34.96	800	3.60	34.95	27.81
781	3.59	34.94	1,000	3.50	34.95	27.82
1,158	3.38	34.95				
Station 2062; Apr. 11; latitude 46°04′ N., longitude 44°38′ W.; depth 3,484 meters; dynamic height 970.940 meters						
0	7.73	34.59	0	7.73	34.59	27.01
24	7.57	34.56	25	7.55	34.56	27.01
47	7.58	34.56	50	7.55	34.56	27.01
71	7.62	34.58	75	7.60	34.58	27.03
94	6.91	34.58	100	6.85	34.58	27.13
141	6.80	34.75	150	6.75	34.77	27.30
189	6.26	34.82	200	6.10	34.82	27.42
283	4.54	34.80	300	4.25	34.77	27.60
290	4.10	34.74	400	3.75	34.85	27.71
434	3.77	34.87	600	4.00	34.95	27.77
577	3.94	34.94	800	4.00	34.99	27.80
736	4.07	35.00	1,000	3.55	34.96	27.82
1,071	3.45	34.95				
Station 2063; Apr. 11; latitude 46°08′ N., longitude 45°25′ W.; depth 2,478 meters; dynamic height 970.838 meters.						
0	4.44	34.37	0	4.44	34.37	27.26
25	4.39	34.38	25	4.39	34.38	27.28
50	4.37	34.38	50	4.37	34.38	27.28
75	4.51	34.48	75	4.51	34.48	27.34
101	4.48	34.66	100	4.50	34.64	27.46
151	4.37	34.78	150	4.35	34.77	27.59
201	5.08	34.94	200	5.05	34.94	27.64
302	4.12	34.92	300	4.15	34.92	27.73
379	3.96	34.93	400	3.95	34.94	27.76
570	3.84	34.96	600	3.80	34.96	27.80
762	3.56	34.96	800	3.50	34.96	27.83
958	3.42	34.97	1,000	3.40	34.97	27.85
1,360	3.24	34.95				
Station 2064; Apr. 11; latitude 46°10′ N., longitude 45°57′ W.; depth 1,051 meters; dynamic height 970.831 meters.						
0	3.18	34.08	0	3.18	34.08	27.16
26	3.24	34.09	25	3.25	34.09	27.15
51	3.60	34.22	50	3.55	34.21	27.23
77	4.00	34.46	75	3.95	34.45	27.37
103	4.57	34.66	100	4.55	34.64	27.46
154	4.20	34.75	150	4.20	34.74	27.58
205	5.21	35.02	200	5.15	35.01	27.69
308	4.16	34.99	300	4.20	34.99	27.78
387	4.06	34.98	400	4.05	34.98	27.79
586	3.63	34.96	600	3.60	34.96	27.82
789	3.44	34.94	800	3.45	34.95	27.82
990	3.35	34.95	1,000	3.35	34.95	27.83
Station 2065; Apr. 11; latitude 46°11′ N., longitude 46°26′ W.; depth 622 meters; dynamic height 970.833 meters.						
0	3.64	34.26	0	3.64	34.26	27.26
19	3.66	34.27	25	3.65	34.26	27.26
39	3.62	34.25	50	3.65	34.26	27.26
58	3.66	34.27	75	3 65	34.26	27.26
78	3.61	34.26	100	3.60	34.26	27.26
117	3.58	34.27	150	3.45	34.66	27.59
155	3.42	34.70	200	3.65	34.80	27.68
233	3.92	34.86	300	4.35	35.00	27.77
301	4.32	35.00	400	4.10	34.98	27.79
492	3.81	34.97	(600)	3.60	34.96	27.82
Station 2066; Apr. 12; latitude 46°13′ N., longitude 46°51′ W.; depth 1,097 meters; dynamic height 970.818 meters.						
0	2.74	33.92	0	2.74	33.92	27.07
21	2.75	33.92	25	2.75	33.92	27.07
42	2.79	33.94	50	2.80	34.00	27.13
63	3.38	34.29	75	3.35	34.52	27.49
84	3.38	34.62	100	3.40	34.67	27.61
126	3.59	34.74	150	3.55	34.78	27.68
167	3.53	34.80	200	3.70	34.84	27.71
251	3.87	34.91	300	3.70	34.94	27.79
304	3.67	34.94	400	3.95	34.97	27.79
458	4.01	34.98	600	3.65	34.97	27.82
613	3.61	34.97	800	3.45	34.96	27.83
798	3.47	34.97	(1,000)	3.40	34.95	27.83

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1936—Continued

Station 2067; Apr. 12; latitude 46°16′ N., longitude 47°20′ W.; depth 631 meters; dynamic height 970.919 meters.

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	−0.13	33.15	0	−0.13	33.15	26.65
22	−.11	33.15	25	−.10	33.15	26.64
44	−.06	33.16	50	−.10	33.16	26.65
67	−.18	33.18	75	−.15	33.28	26.75
89	−.03	33.61	100	.55	33.81	27.14
133	1.76	34.27	150	2.10	34.38	27.49
177	2.48	34.52	200	2.70	34.60	27.61
266	3.16	34.76	300	3.40	34.81	27.72
283	3.32	34.81	400	3.80	34.89	27.74
463	3.96	34.92	(600)	3.75	34.94	27.78

Station 2068; Apr. 12; latitude 46°19′ N., longitude 47°52′ W.; depth 165 meters; dynamic height 971.017 meters.

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	−0.65	32.82	0	−0.65	32.81	26.39
25	−.67	32.80	25	−.67	32.81	26.39
50	−.68	32.82	50	−.68	32.82	26.40
75	−.70	32.96	75	−.70	32.96	26.52
99	−.52	33.24	100	−.55	33.25	26.73
149	−.06	33.53	150	−.05	33.54	26.95

Station 2069; Apr. 12; latitude 46°19′ N., longitude 48°13′ W.; depth 114 meters; dynamic height 970.991 meters.

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	0.18	33.05	0	0.18	33.05	26.54
18	.38	33.12	25	.45	33.12	26.59
44	.47	33.12	50	.40	33.12	26.59
71	−.08	33.19	75	−.05	33.20	26.68
97	.02	33.52	100	.05	33.59	26.99

Station 2070; Apr. 12; latitude 46°22′ N., longitude 48°40′ W.; depth 88 meters; dynamic height 970.988 meters.

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	1.31	33.30	0	1.31	33.30	26.68
23	1.27	33.30	25	1.25	33.30	26.68
47	1.22	33.29	50	1.20	33.29	26.68
70	1.16	33.30	75	1.15	33.30	26.69

Station 2071; Apr. 12; latitude 46°22′ N., longitude 48°55′ W.; depth 66 meters; dynamic height 970.997 meters.

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	1.77	33.19	0	1.77	33.19	26.57
27	1.74	33.19	25	1.75	33.19	26.57
55	1.67	33.19	50	1.70	33,19	26.57

Station 2072; Apr. 12; latitude 46°12′ N., longitude 48°39′ W.; depth 89 meters; dynamic height 970.992 meters.

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	1.36	33.30	0	1.36	33.30	26.68
27	1.30	33.30	25	1.30	33.30	26.68
53	1.18	33.29	50	1.20	33.29	26.68
80	.74	33.34	75	.85	33.32	26.73

Station 2073; Apr. 12; latitude 45°57′ N., longitude 48°20′ W.; depth 115 meters; dynamic height 970.999 meters.

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	−0.10	32.87	0	−0.10	32.87	26.41
23	.48	33.08	25	.45	33.08	26.56
46	.45	33.10	50	.35	33.11	26.59
69	−.01	33.22	75	−.05	33.27	26.73
92	−.08	33.47	(100)	−.10	33.55	26.96

Station 2074; Apr. 12; latitude 45°45′ N., longitude 47°56′ W.; depth 167 meters; dynamic height 971.014 meters.

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	−0.49	32.78	0	−0.49	32.78	26.36
26	−.58	32.83	25	−.55	32.83	26.40
51	−.75	32.92	50	−.75	32.91	26.47
77	−.56	33.18	75	−.55	33.16	26.67
103	−.14	33.44	100	−.15	33.42	26.87
154	−.03	33.55	150	−.05	33.54	26.95

Station 2075; Apr 12–13; latitude 45°39′ N., longitude 47°44′ W.; depth 604 meters; dynamic height 970.949 meters.

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	−0.46	33.03	0	−0.46	33.03	26.56
24	−.42	33.04	25	−.45	33.04	26.57
48	−.35	33.06	50	−.35	33.06	26.57
72	−.43	33.35	75	−.45	33.36	26.83
96	−.08	33.60	100	.05	33.64	27.03
144	1.53	34.09	150	1.60	34.11	27.31
193	2.01	34.36	200	2.05	34.38	27.50
289	2.88	34.65	300	3.05	34.68	27.65
327	3.32	34.75	400	3.60	34.81	27.70
510	3.60	34.82	(600)	3.60	34.92	27.79

Station 2076; Apr. 13; latitude 45°36′ N., longitude 47°40′ W.; depth 1,097 meters; dynamic height 970.906 meters.

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	0.29	33.24	0	0.29	33.24	26.70
24	.38	33.24	25	.30	33.24	26.70
49	.23	33.32	50	.25	33.33	26.77
73	.51	33.75	75	.55	33.77	27.11
97	1.15	33.98	100	1.20	34.02	27.27
146	2.24	34.37	150	2.30	34.39	27.48
195	2.59	34.54	200	2.60	34.55	27.58
292	3.04	34.72	300	3.25	34.76	27.69
306	3.45	34.80	400	3.90	34.89	27.73
381	3.73	34.80	(600)	3.80	34.94	27.78
403	3.92	34.89	(800)	3.45	34.94	27.81
476	3.96	34.92	(1,000)	3.30	34.95	27.84

Station 2077; Apr. 13; latitude 45°32′ N., longitude 47°32′ W.; depth 1,422 meters; dynamic height 970.858 meters.

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	1.02	33.36	0	1.02	33.36	26.75
26	1.59	33.52	25	1.55	33.51	26.84
52	2.08	33.94	50	2.00	33.85	27.07
79	2.50	34.34	75	2.40	34.30	27.40
105	3.13	34.52	100	3.05	34.50	27.50
157	2.84	34.62	150	2.85	34.61	27.61
210	3.32	34.75	200	3.25	34.73	27.67
315	3.88	34.90	300	3.85	34.89	27.73
420	3.78	34.93	400	3.80	34.92	27.77
629	3.58	34.94	600	3.60	34.94	27.80
836	3.44	34.93	800	3.45	34.93	27.81
1,026	3.32	34.92	1,000	3.35	34.92	27.81
1,384	3.28	34.92				

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1936—Continued

Station 2078; Apr. 13; latitude 45°28′ N., longitude 47°25′ W.; depth 1,902 meters; dynamic height 970.900 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	2.06	33.27	0	2.06	33.27	26.61
26	3.19	33.48	25	3.15	33.47	26.68
52	6.41	34.39	50	6.35	34.32	26.99
78	6.03	34.56	75	6.05	34.56	27.22
104	3.77	34.41	100	3.80	34.41	27.36
156	5.59	34.82	150	5.50	34.81	27.49
209	4.33	34.76	200	4.45	34.76	27.57
313	4.25	34.90	300	4.25	34.89	27.69
410	3.89	34.91	400	3.95	34.91	27.74
615	3.62	34.92	600	3.65	34.92	27.78
820	3.47	34.93	800	3.50	34.93	27.81
1,025	3.37	34.94	1,000	3.35	34.94	27.82
1,433	3.27	34.92				

Station 2079; Apr. 13; latitude 45°34′ N., longitude 46°48′ W.; depth 2,917 meters; dynamic height 970.927 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	6.53	34.37	0	6.53	34.37	27.01
25	6.52	34.37	25	6.52	34.37	27.01
50	6.47	34.36	50	6.47	34.36	27.01
76	6.51	34.37	75	6.50	34.37	27.01
101	6.81	34.55	100	6.80	34.54	27.10
151	6.27	34.77	150	6.35	34.77	27.35
202	5.04	34.74	200	5.05	34.74	27.48
303	5.17	34.95	300	5.15	34.95	27.64
386	4.62	34.95	400	4.60	34.95	27.70
578	4.24	34.99	600	4.20	34.99	27.78
770	3.81	34.98	800	3.80	34.98	27.82
967	3.64	34.98	1,000	3.60	34.98	27.84
1,368	3.41	34.96				

Station 2080; Apr. 13; latitude 45°21′ N., longitude 45°55′ W.; depth 3,447 meters; dynamic height 970.939 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	8.02	34.66	0	8.02	34.66	27.03
24	8.03	34.67	25	8.05	34.67	27.03
47	8.05	34.67	50	8.05	34.67	27.03
71	8.07	34.68	75	8.05	34.68	27.04
95	8.08	34.68	100	8.05	34.69	27.04
142	7.47	34.83	150	7.40	34.84	27.25
189	6.86	34.85	200	6.70	34.86	27.37
284	5.66	34.96	300	5.30	34.94	27.61
294	5.24	34.92	400	4.65	34.97	27.72
450	4.49	34.98	600	4.20	35.00	27.79
611	4.17	35.00	800	3.90	35.00	27.82
786	3.91	35.00	1,000	3.55	34.97	27.83
1,167	3.40	34.95				

Station 2081; Apr. 13; latitude 44°50′ N., longitude 46°06′ W.; depth 3,402 meters; dynamic height 970.965 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	8.41	34.67	0	8.41	34.67	26.98
24	8.51	--------	25	8.55	34.70	26.97
48	9.09	34.88	50	9.05	34.88	27.04
72	8.92	34.86	75	8.90	34.86	27.04
96	8.83	34.87	100	8.80	34.86	27.06
144	6.80	34.67	150	6.65	34.67	27.23
191	5.86	34.72	200	5.70	34.73	27.40
287	5.39	34.88	300	5.10	34.86	27.57
281	4.96	34.83	400	4.85	34.91	27.64
456	-------	34.92	600	4.45	35.00	27.76
654	4.36	35.02	800	4.10	35.01	27.81
839	4.04	35.01	1,000	3.75	34.98	27.82
1,234	3.42	34.95				

Station 2082; Apr. 14; latitude 44°24′ N., longitude 46°15′ W.; depth 3,676 meters; dynamic height 971.038 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	12.55	35.51	0	12.55	35.51	26.90
20	12.54	35.52	25	12.55	35.52	26.90
39	12.55	35.51	50	12.50	35.50	26.90
59	12.43	35.49	75	12.55	35.51	26.90
78	12.56	35.51	100	12.55	35.51	26.90
117	12.47	35.50	150	12.20	35.43	26.90
157	12.10	35.41	200	11.15	35.35	27.04
235	10.01	35.30	300	6.95	35.10	27.53
248	*9.52	35.26	400	4.85	34.88	27.62
388	4.87	34.87	600	4.65	35.01	27.75
538	4.80	35.01	800	4.05	34.99	27.79
698	4.31	35.01	1,000	3.65	34.96	27.81
1,052	3.56	34.94				

Station 2083; Apr. 14; latitude 44°36′ N., longitude 46°53′ W.; depth 3,621 meters; dynamic height 970.981 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	8.29	34.68	0	8.29	34.68	27.00
24	8.29	34.68	25	8.30	34.68	27.00
49	8.45	34.74	50	8.50	34.76	27.03
73	10.18	35.10	75	10.15	35.11	27.03
97	10.70	35.22	100	10.65	35.22	27.03
146	7.60	34.79	150	7.60	34.79	27.18
195	8.23	34.96	200	8.25	34.95	27.22
292	4.71	34.72	300	4.75	34.73	27.52
346	5.11	34.91	400	4.85	34.93	27.66
523	4.29	34.96	600	4.15	34.97	27.77
703	3.99	34.97	800	3.80	34.96	27.80
890	3.63	34.95	1,000	3.55	34.95	27.81
1,278	3.50	34.96				

Station 2084; Apr. 14; latitude 44°54′ N., longitude 47°29′ W.; depth 3,640 meters; dynamic height 970.995 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	0.38	32.90	0	0.38	32.90	26.42
26	.18	32.98	25	.20	32.99	26.50
52	1.66	33.36	50	1.60	33.31	26.67
77	.02	33.62	75	.05	33.61	27.01
103	.26	33.70	100	.20	33.69	27.06
155	2.35	34.18	150	2.05	34.12	27.29
207	6.10	34.88	200	6.05	34.87	27.47
310	4.81	34.87	300	4.85	34.87	27.61
416	4.87	35.00	400	4.90	34.99	27.70
594	4.74	34.94	600	4.70	34.96	27.70
753	4.21	34.94	800	4.05	34.94	27.75
953	3.66	34.94	1,000	3.60	34.94	27.80
1,367	3.31	34.94				

Station 2085; Apr. 14; latitude 44°57′ N., longitude 47°55′ W.; depth 3,182 meters; dynamic height 970.903 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	0.79	33.02	0	0.79	33.02	26.49
26	.33	33.06	25	.35	33.06	26.54
52	.35	33.48	50	.30	33.39	26.81
78	.96	33.96	75	.90	33.94	27.22
104	1.51	34.17	100	1.40	34.13	27.35
156	2.96	34.56	150	2.75	34.52	27.55
209	4.28	34.81	200	4.20	34.78	27.65
313	4.24	34.90	300	4.25	34.89	27.62
419	4.18	34.96	400	4.20	34.95	27.79
626	-------	34.96	600	3.90	34.96	27.79
832	3.54	34.94	800	3.60	34.94	27.80
1,039	3.36	34.92	1,000	3.40	34.92	27.81
1,450	3.24	34.93				

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1936—Continued

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
Station 2086; Apr. 14; latitude 44°58′ N., longitude 48°33′ W.; depth 1,471 meters; dynamic height 970.880 meters						
0	3.16	33.57	0	3.16	33.57	26.77
26	3.85	33.74	25	3.80	33.76	26.84
52	6.49	34.38	50	6.45	34.38	27.03
77	4.37	34.38	75	4.35	34.38	27.28
103	4.31	34.57	100	4.30	34.54	27.41
155	4.32	34.75	150	4.30	34.73	27.57
207	4.27	34.85	200	4.25	34.84	27.65
310	3.80	34.86	300	3.80	34.86	27.72
392	3.95	34.93	400	3.95	34.93	27.76
591	3.73	34.94	600	3.75	34.94	27.78
791	3.52	34.92	800	3.55	34.92	27.79
991	3.43	34.93	1,000	3.45	34.93	27.81
1,393	3.28	34.92				
Station 2087; Apr. 14; latitude 44°59′ N., longitude 49°03′ W.; depth 631 meters; dynamic height 971.013 meters						
0	−0.51	32.96	0	−0.51	32.96	26.51
26	−.52	33.00	25	−.55	33.00	26.54
52	−.82	33.22	50	−.80	33.19	26.70
79	−.37	33.41	75	−.40	33.38	26.85
105	.05	33.60	100	−.05	33.56	26.97
157	1.08	33.97	150	.95	33.92	27.20
209	1.72	34.20	200	1.65	34.16	27.35
314	2.82	34.60	300	2.70	34.55	27.57
396	3.41	34.78	400	3.45	34.78	27.69
595	3.68	34.83	600	3.65	34.83	27.71
Station 2088; Apr. 15; latitude 44°59′ N., longitude 49°07′ W.; depth 224 meters; dynamic height 971.048 meters						
0	−0.42	32.93	0	−0.42	32.93	26.48
17	−.35	33.18	25	−.30	33.22	26.70
43	−.24	33.28	50	−.20	33.31	26.77
68	−.13	33.37	75	−.15	33.39	26.84
94	−.12	33.42	100	−.10	33.42	26.86
145	−.06	33.44	150	.00	33.46	26.89
196	.96	33.94	(200)	1.15	34.01	27.26
Station 2089; Apr. 15; latitude 44°59.5′ N., longitude 49°18′ W.; depth 88 meters; dynamic height 971.062 meters						
0	−0.14	32.98	0	−0.14	32.98	26.51
26	−.26	33.04	25	−.25	33.04	26.56
53	−.18	33.11	50	−.20	33.11	26.61
79	−.15	33.12	75	−.15	33.12	26.62
Station 2090; Apr. 15; latitude 45°00′ N., longitude 49°35.5′ W.; depth 66 meters; dynamic height 971.058 meters						
0	1.15	33.03	0	1.15	33.03	26.48
26	1.08	33.06	25	1.05	33.06	26.51
52	.39	33.30	50	.50	33.26	26.69

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
Station 2091; Apr. 15; latitude 44°16′ N., longitude 49°21′ W.; depth 55 meters; dynamic height 971.072 meters						
0	1.77	33.21	0	1.77	33.21	26.58
22	1.66	33.20	25	1.65	33.20	26.58
44	1.67	33.18	(50)	1.65	33.20	26.58
Station 2092; Apr. 15; latitude 44°10′ N., longitude 49°10′ W.; depth 91 meters						
[No temperatures or salinities]						
Station 2093; Apr. 15; latitude 44°08′ N., longitude 49°03′ W.; depth 220 meters; dynamic height 971.063 meters						
0	0.16	33.02	0	0.16	33.02	26.52
26	−.18	33.06	25	−.20	33.06	26.57
52	.02	33.48	50	0.00	33.47	26.90
78	.02	33.51	75	0.00	33.51	26.93
104	.04	33.54	100	.05	33.54	26.95
156	.09	33.56	150	.10	33.56	26.96
208	.42	33.77	200	.35	33.73	27.09
Station 2094; Apr. 15; latitude 44°09′ N. longitude 49°10′ W.; depth 89 meters; dynamic height 971.070 meters						
0	1.09	33.00	0	1.09	33.00	26.46
28	.62	33.04	25	.65	33.04	26.51
56	.08	33.44	50	.15	33.31	26.75
84	.13	33.54	75	.10	33.52	26.93
Station 2095; Apr. 15; latitude 44°07′ N., longitude 48°56′ W.; depth 631 meters; dynamic height 971.012 meters						
0	0.22	33.08	0	0.22	33.08	26.57
25	−.14	33.16	25	−.14	33.16	26.66
50	−.17	33.32	50	−.17	33.32	26.78
76	−.02	33.62	75	−.05	33.62	27.02
101	.23	33.71	100	.20	33.70	27.07
151	.67	33.88	150	.65	33.88	27.19
202	.67	33.88	200	.65	33.88	27.19
303	2.05	34.30	300	2.00	34.28	27.42
393	2.73	34.60	400	2.80	34.61	27.61
593	3.67	34.88	600	3.70	34.88	27.75
Station 2096; Apr. 15; latitude 44°05′ N., longitude 48°47′ W.; depth 2,012 meters; dynamic height 970.931 meters						
0	0.54	33.10	0	0.54	33.10	26.57
25	−.03	33.14	25	−.03	33.14	26.63
49	−.04	33.24	50	−.05	33.26	26.72
74	−.07	33.70	75	−.05	33.71	27.09
99	.92	33.94	100	.95	33.95	27.22
148	1.66	34.21	150	1.70	34.22	27.39
197	2.23	34.42	200	2.25	34.43	27.52
296	3.02	34.68	300	3.05	34.69	27.65
363	3.54	34.84	400	3.70	34.88	27.75
551	3.91	34.94	600	3.90	34.94	27.77
743	3.82	34.96	800	3.80	34.96	27.80
930	3.78	34.96	(1,000)	3.70	34.96	27.81

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1936—Continued

Station 2097; Apr. 15; latitude 43°57′ N., longitude 48°23′ W.; depth 3,383 meters; dynamic height 970.880 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	6.39	34.13	0	6.39	34.13	26.85
26	5.82	34.14	25	5.85	34.14	26.91
52	5.74	34.18	50	5.75	34.17	26.95
79	3.47	34.26	75	3.60	34.24	27.24
105	4.93	34.58	100	4.80	34.55	27.36
157	4.70	34.74	150	4.70	34.72	27.51
209	5.03	34.88	200	5.00	34.87	27.60
314	4.41	34.91	300	4.45	34.90	27.68
418	4.45	35.02	400	4.45	35.01	27.77
625	4.05	35.01	600	4.10	35.01	27.81
831	3.76	35.00	800	3.80	35.00	27.83
1,038	3.59	34.98	1,000	3.60	34.98	27.84
1,449	3.33	34.96				

Station 2098; Apr. 15–16; latitude 43°48′ N., longitude 47°46′ W.; depth (no sounding); dynamic height 970.869 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	6.02	34.09	0	6.02	34.09	26.85
25	5.78	34.10	25	5.78	34.10	26.89
49	5.69	34.15	50	5.65	34.16	26.95
74	4.77	34.55	75	4.75	34.55	27.37
99	4.74	34.62	100	4.70	34.62	27.43
148	4.23	34.70	150	4.25	34.71	27.55
197	4.22	34.82	200	4.25	34.83	27.65
296	4.54	34.97	300	4.55	34.97	27.73
358	4.43	34.98	400	4.40	34.98	27.75
541	4.11	35.01	600	4.00	35.00	27.81
727	3.78	34.98	800	3.75	34.98	27.82
910	3.70	34.98	(1,000)	3.65	34.97	27.82

Station 2099; Apr. 16; latitude 43°37′ N., longitude 47°07′ W.; depth 4,152 meters; dynamic height 970.935 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	7.80	34.39	0	7.80	34.39	26.84
21	8.04	34.44	25	8.10	34.51	26.89
43	8.40	34.76	50	7.75	34.66	27.06
64	4.19	34.14	75	5.90	34.43	27.14
85	7.93	34.84	100	8.90	35.05	27.19
128	9.65	35.24	150	8.65	35.09	27.26
171	7.83	34.98	200	7.20	34.99	27.40
256	6.32	35.02	300	5.90	35.02	27.60
281	6.18	35.02	400	5.10	35.03	27.71
437	4.88	35.03	600	4.45	35.04	27.79
604	4.43	35.04	800	3.70	34.98	27.83
774	3.77	34.98	1,000	3.50	34.97	27.84
1,135	3.45	34.97				

Station 2100; Apr. 16; latitude 43°27′ N., longitude 46°31′ W.; depth 4,326 meters; dynamic height 970.904 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	6.13	33.98	0	6.13	33.98	26.76
26	6.08	33.98	25	6.05	33.98	26.77
50	4.97	34.06	50	4.95	34.06	26.96
76	3.34	34.16	75	3.35	34.16	27.20
101	3.13	34.37	100	3.15	34.36	27.38
152	5.87	34.80	150	5.80	34.78	27.43
203	6.05	34.93	200	6.05	34.93	27.52
304	5.29	35.03	300	5.30	35.03	27.69
388	5.01	35.06	400	5.00	35.06	27.75
598	------	35.04	600	4.55	35.04	27.78
819	3.99	35.02	800	4.00	35.02	27.83
1,040	3.63	34.98	1,000	3.70	34.98	27.83
1,501	3.39	34.98				

Station 2101; Apr. 16; latitude 43°04′ N., longitude 46°46′ W.; depth 3,923 meters; dynamic height 970.889 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	7.39	34.24	0	7.39	34.24	26.78
27	7.20	34.30	25	7.25	34.30	26.85
54	2.69	34.04	50	2.80	34.06	27.18
81	3.08	34.28	75	2.95	34.22	27.29
107	3.27	34.38	100	3.20	34.36	27.38
162	5.36	34.83	150	4.95	34.74	27.49
216	5.08	34.89	200	5.10	34.87	27.58
323	5.15	35.03	300	5.15	35.01	27.69
518	4.47	35.04	400	4.90	35.04	27.74
712	4.21	35.02	600	4.35	35.03	27.80
862	3.86	34.99	800	4.05	35.00	27.80
1,086	3.54	34.97	1,000	3.60	34.98	27.84
1,543	3.28	34.95				

Station 2102; Apr. 16; latitude 42°40′ N., longitude 46°57′ W.; depth 3,951 meters; dynamic height 970.990 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	3.68	33.33	0	3.68	33.33	26.51
25	5.94	34.02	25	5.94	34.02	26.81
51	8.44	34.64	50	8.40	34.61	26.93
76	10.11	35.04	75	10.10	35.03	26.98
102	10.31	35.14	100	10.30	35.14	27.03
151	8.48	34.92	150	8.55	34.92	27.15
202	6.63	34.72	200	6.75	34.72	27.26
304	5.67	34.92	300	5.60	34.90	27.54
307	5.55	34.92	400	5.20	35.02	27.69
459	5.00	35.04	600	4.65	35.04	27.77
609	4.64	35.04	800	4.20	35.02	27.80
780	4.24	35.03	1,000	3.75	35.00	27.83
1,144	3.55	34.98				

Station 2103; Apr. 16; latitude 42°54′ N., longitude 47°37′ W.; depth 3,548 meters; dynamic height 970.929 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	6.88	34.18	0	6.88	34.18	26.81
25	7.36	34.34	25	7.36	34.34	26.87
51	7.47	34.40	50	7.45	34.40	26.90
76	8.01	34.82	75	8.00	34.81	27.14
102	7.91	34.86	100	7.95	34.86	27.19
151	6.66	34.84	150	6.65	34.84	27.36
202	5.93	34.84	200	5.95	34.84	27.45
304	4.64	34.87	300	4.70	34.87	27.63
399	4.47	34.97	400	4.45	34.97	27.74
591	4.37	35.02	600	4.35	35.02	27.79
778	3.77	34.96	800	3.75	34.96	27.80
980	3.67	34.99	1,000	3.65	34.99	27.83
1,392	3.32	34.95				

Station 2104; Apr. 17; latitude 43°08′ N., longitude 48°16′ W.; depth 3,392 meters; dynamic height 970.910 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	4.41	33.69	0	4.41	33.69	26.73
28	6.10	34.13	25	6.05	34.12	26.88
55	6.12	34.34	50	6.10	34.31	27.02
83	7.78	34.78	75	7.40	34.65	27.11
110	6.99	34.75	100	7.20	34.76	27.22
166	5.81	34.77	150	6.15	34.77	27.38
221	4.30	34.72	200	4.85	34.74	27.51
331	3.94	34.84	300	3.95	34.80	27.65
446	4.09	34.96	400	4.00	34.92	27.75
665	3.85	34.98	600	3.95	34.98	27.80
882	3.63	34.97	800	3.70	34.97	27.82
1,107	3.47	34.95	1,000	3.55	34.96	27.82
1,560	3.29	34.95				

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1936—Continued

Station 2105; Apr. 17; latitude 43°23′ N., longitude 49°00′ W.; depth 1,765 meters; dynamic height 970.914 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	1.19	33.04	0	1.19	33.04	26.48
26	7.91	34.52	25	7.90	34.52	26.93
51	6.17	34.41	50	6.30	34.42	27.08
77	4.42	34.21	75	4.45	34.21	27.13
103	4.52	34.32	100	4.50	34.31	27.21
154	3.45	34.42	150	3.45	34.41	27.39
206	5.48	34.92	200	5.45	34.90	27.56
309	4.51	34.92	300	4.60	34.92	27.68
416	4.18	34.91	400	4.20	34.91	27.72
623	3.89	34.95	600	3.90	34.95	27.78
830	3.56	34.94	800	3.55	34.94	27.80
1,036	3.43	34.95	1,000	3.45	34.95	27.82
1,442	3.35	34.96				

Station 2106; Apr. 17; latitude 43°24′ N., longitude 50°08′ W.; depth 68 meters; dynamic height 971.055 meters.

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	2.34	33.24	0	2.34	33.24	26.56
25	1.99	33.24	25	1.99	33.24	26.59
51	1.62	33.39	50	1.65	33.38	26.73

Station 2107; Apr. 17; latitude 43°00′ N., longitude 50°07′ W.; depth 91 meters; dynamic height 971.012 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	0.82	32.98	0	0.82	32.98	26.47
24	.30	33.08	25	.30	33.08	26.57
49	.49	33.17	50	.50	33.18	26.63
73	.24	33.34	75	.25	33.34	26.78

Station 2108; Apr. 17; latitude 42°48′ N., longitude 50°07′ W.; depth 622 meters; dynamic height 970.989 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	1.11	32.80	0	1.11	32.80	26.30
26	.04	33.18	25	.05	33.17	26.66
52	.02	33.43	50	.00	33.40	26.84
78	.22	33.63	75	.20	33.60	26.99
104	.43	33.73	100	.40	33.71	27.07
156	2.15	34.02	150	2.10	33.99	27.17
209	2.27	34.26	200	2.25	34.23	27.36
313	2.69	34.53	300	2.60	34.49	27.53
409	3.42	34.79	400	3.40	34.77	27.69
615	3.73	34.88	600	3.70	34.87	27.74

Station 2109; Apr. 18; latitude 42°30′ N., longitude 50°07· W.; depth 2,935 meters; dynamic height 970.937 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	2.70	33.09	0	2.70	33.09	26.41
26	1.90	33.37	25	1.90	33.37	26.71
51	1.16	33.56	50	1.15	33.55	26.89
77	.69	33.71	75	.70	33.70	27.04
103	2.14	33.98	100	1.80	33.93	27.15
154	4.01	34.47	150	4.00	34.44	27.36
205	3.70	34.60	200	3.70	34.59	27.51
308	3.74	34.78	300	3.75	34.77	27.65
412	3.78	34.88	400	3.80	34.87	27.73
616	3.84	34.94	600	3.85	34.94	27.77
819	3.71	34.95	800	3.70	34.95	27.80
1,023	3.57	34.94	1,000	3.60	34.94	27.80
1,430	3.36	34.92				

Station 2110; Apr. 18; latitude 42°00′ N., longitude 50°07′ W.; depth 3,493 meters.; dynamic height 970.945 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	2.88	33.04	0	2.88	33.04	26.36
10	2.55	33.04	25	1.81	33.16	26.54
25	1.81	33.16	50	3.05	33.85	26.98
35	3.99	33.56	75	2.75	34.14	27.24
60	2.34	33.98	100	3.85	34.39	27.34
153	6.06	34.77	150	6.05	34.75	27.37
203	5.84	34.85	200	5.85	34.85	27.47
305	5.37	34.98	300	5.40	34.98	27.64
380	4.49	34.90	400	4.45	34.90	27.68
570	4.23	34.92	(600)	4.20	34.93	27.74
			(800)	4.00	35.00	27.81
			(1,000)	3.70	34.98	27.83

Station 2111; Apr. 18; latitude 41°40′ N., longitude 49°18′ W.; depth 2,515 meters; dynamic height 971.083 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	8.98	34.12	0	8.98	34.12	26.45
26	13.10	35.42	25	13.10	35.42	26.72
53	12.72	35.47	50	12.80	35.47	26.81
79	11.74	35.32	75	11.90	35.35	26.90
106	11.14	35.22	100	11.25	35.23	26.92
158	11.01	35.32	150	11.05	35.31	27.03
211	10.18	35.29	200	10.40	35.31	27.14
317	7.23	34.98	300	7.50	34.99	27.36
423	6.48	35.02	400	6.65	35.02	27.51
630	4.32	34.92	600	4.45	34.93	27.71
834	4.20	35.00	800	4.25	34.99	27.77
1,044	3.87	34.98	1,000	3.95	34.98	27.80
1,466	3.46	34.94				

Station 2112; Apr. 18; latitude 41°19′ N., longitude 48°32′ W.; depth 2,944 meters; dynamic height 970.982 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	1.12	32.90	0	1.12	32.90	26.38
24	1.15	33.03	25	1.15	33.04	26.49
48	4.12	33.72	50	4.30	33.80	26.82
72	4.83	34.12	75	4.80	34.12	27.02
96	3.68	33.98	100	3.55	33.97	27.04
144	2.51	33.92	150	2.40	33.92	27.10
191	1.55	34.12	200	1.70	34.17	27.35
287	3.97	34.71	300	3.95	34.73	27.60
383	3.78	34.79	400	3.80	34.81	27.68
580	4.49	35.02	600	4.50	35.02	27.77
781	3.97	35.00	800	3.95	35.00	27.81
982	3.78	35.00	1,000	3.75	35.00	27.83
1,392	3.42	34.97				

Station 2113; Apr. 18–19; latitude 41°00′ N., longitude 47°40′ W.; depth 3,411 meters; dynamic height 971.149 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	14.39	35.62	0	14.39	35.62	26.60
24	14.11	35.67	25	14.10	35.67	26.70
49	14.11	35.71	50	14.10	35.71	26.73
73	14.09	35.77	75	14.05	35.77	26.79
98	13.63	35.69	100	13.55	35.67	26.82
147	12.14	35.42	150	12.05	35.41	26.92
195	11.25	35.26	200	11.20	35.26	26.96
293	10.42	35.34	300	10.30	35.33	27.18
358	*8.92	35.19	400	7.85	35.12	27.41
541	5.57	35.00	600	5.25	35.01	27.68
727	4.83	35.05	800	4.65	35.05	27.78
916	4.33	35.05	1,000	4.15	35.04	27.82
1,304	3.69	35.00				

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1936—Continued

Station 2114; Apr. 19; latitude 41°48′ N., longitude 47°13′ W.; depth 4,326 meters; dynamic height 971.262 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	15.26	35.84	0	15.26	35.84	26.57
24	15.25	35.84	25	15.25	35.84	26.57
48	14.83	35.82	50	14.85	35.82	26.65
71	14.86	35.86	75	14.85	35.87	26.69
95	15.01	35.92	100	15.00	35.91	26.69
143	13.31	35.60	150	13.25	35.59	26.81
191	12.85	35.57	200	12.70	35.54	26.89
286	11.68	35.38	300	11.55	35.38	26.99
256	*11.83	35.36	400	10.25	35.34	27.19
389	10.45	35.36	600	6.60	35.07	27.55
526	7.76	35.14	800	4.90	35.04	27.74
667	5.80	35.04	(1,000)	4.20	35.03	27.81
959	4.34	35.03				

Station 2115; Apr. 19: latitude 42°03′ N., longitude 47°55′ W.; depth 3,841 meters; dynamic height 971.131 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	11.99	35.06	0	11.99	35.06	26.66
24	12.30	35.19	25	12.30	35.20	26.69
48	14.61	35.89	50	14.60	35.89	26.76
72	14.56	35.90	75	14.40	35.90	26.81
95	12.39	35.40	100	12.30	35.39	26.85
144	11.58	35.27	150	11.45	35.26	26.92
192	10.69	35.16	200	10.60	35.16	26.99
287	9.89	35.27	300	9.70	35.26	27.22
331	*9.21	35.20	400	7.60	35.10	27.43
472	6.23	35.04	600	5.30	35.04	27.69
621	5.17	35.04	800	4.40	35.04	27.79
779	4.44	35.04	1,000	4.00	35.02	27.83
1,120	3.81	35.00				

Station 2116; Apr. 19; latitude 42°19′ N., longitude 48°37′ W.; depth 3,383 meters; dynamic height 970.933 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	7.53	33.95	0	7.53	33.95	26.53
27	4.82	33.93	25	4.80	33.93	26.88
54	6.50	34.48	50	6.20	34.38	27.06
81	7.30	34.75	75	7.10	34.68	27.18
108	9.16	35.20	100	8.90	35.16	27.28
163	7.95	35.08	150	8.25	35.11	27.34
216	6.67	34.98	200	7.05	35.01	27.44
324	4.51	34.86	300	4.80	34.87	27.62
574	4.15	34.99	400	4.30	34.88	27.68
859	3.89	35.01	600	4.15	35.00	27.79
1,144	3.63	34.99	800	3.95	35.01	27.82
1,431	3.42	34.97	1,000	3.80	35.00	27.83
2,008	3.21	34.96				

Station 2117; Apr. 19; latitude 42°34′ N., longitude 49°15′ W.; depth 2,862 meters; dynamic height 970.913 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	1.95	32.86	0	1.95	32.86	26.28
26	.54	33.30	25	.55	33.32	26.74
52	3.12	33.96	50	2.85	33.89	27.03
77	3.82	34.19	75	3.80	34.17	27.17
103	5.70	34.62	100	5.55	34.57	27.29
155	6.04	34.84	150	6.05	34.83	27.44
207	5.73	34.93	200	5.80	34.92	27.54
310	4.68	34.95	300	4.75	34.95	27.68
415	4.72	35.01	400	4.70	35.00	27.73
620	3.99	34.98	600	4.05	34.98	27.79
825	3.72	34.98	800	3.75	34.98	27.82
1,029	3.51	34.96	1,000	3.55	34.96	27.82
1,436	3.30	34.95				

Station 2118; May 7; latitude 46°54′ N., longitude 48°37′ W.; depth 96 meters; dynamic height 971.005 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	1.01	32.81	0	1.01	32.81	26.32
26	1.37	33.02	25	1.35	33.02	26.46
53	.71	33.07	50	.80	33.06	26.52
79	−.08	33.42	75	.05	33.38	26.82

Station 2119; May 7; latitude 46°54′ N., longitude 48°08′ W.; depth 115 meters; dynamic height 971.006 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	1.12	32.84	0	1.12	32.84	26.33
26	1.09	32.94	25	1.10	32.94	26.41
51	.74	33.18	50	.75	33.17	26.61
77	−.26	33.33	75	−.25	33.32	26.78
103	.01	33.50	100	.00	33.48	26.90

Station 2120; May 7; latitude 46°53′ N., longitude 47°39′ W.; depth 169 meters; dynamic height 971.030 meters.

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	0.31	32.75	0	0.31	32.75	26.30
26	−.15	32.76	25	−.15	32.76	26.33
52	−.69	32.84	50	−.65	32.83	26.41
78	−.70	32.91	75	−.70	32.90	26.46
104	−.62	33.23	100	−.65	33.16	26.67
156	.13	33.63	150	.05	33.60	27.00

Station 2121; May 7; latitude 46°51′ N., longitude 47°14′ W.; depth 668 meters; dynamic height 970.943 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	0.40	32.92	0	0.40	32.92	26.43
24	.15	32.98	25	.15	32.99	26.50
48	.14	33.20	50	.15	33.24	26.70
73	1.31	33.70	75	1.35	33.71	27.01
97	1.62	33.80	100	1.65	33.82	27.07
145	1.98	34.31	150	2.05	34.35	27.47
193	2.65	34.52	200	2.70	34.53	27.55
290	3.00	34.68	300	3.05	34.69	27.65
323	3.18	34.72	400	3.55	34.80	27.69
512	3.74	34.90	(600)	3.75	34.94	27.78

Station 2122; May 7; latitude 46°51′ N., longitude 47°04′ W.; depth, 1,143 meters; dynamic height 970.871 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	1.26	33.20	0	1.26	33.20	26.61
26	1.61	33.78	25	1.60	33.78	27.04
52	1.41	33.92	50	1.40	33.90	27.15
78	1.49	34.08	75	1.45	34.07	27.29
104	2.10	34.30	100	2.00	34.27	27.41
156	3.10	34.68	150	3.05	34.64	27.61
207	3.24	34.76	200	3.25	34.75	27.68
311	3.59	34.86	300	3.55	34.85	27.73
409	3.78	34.90	400	3.75	34.90	27.75
612	3.74	34.93	600	3.75	34.93	27.77
815	3.76	34.95	800	3.75	34.95	27.79
1,014	3.50	34.95	1,000	3.55	34.95	27.81

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1936—Continued

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
Station 2123; May 8; latitude 46°51′ N., longitude 46°36′ W.; depth 631 meters; dynamic height 970.815 meters						
0	4.96	34.38	0	4.96	34.38	27.21
26	4.80	34.36	25	4.80	34.36	27.21
52	4.41	34.43	50	4.45	34.42	27.30
78	4.31	34.50	75	4.30	34.49	27.37
104	3.72	34.64	100	3.80	34.63	27.53
156	3.92	34.80	150	3.90	34.78	27.64
209	4.32	34.92	200	4.30	34.91	27.70
313	4.32	34.99	300	4.35	34.99	27.76
414	3.87	34.96	400	3.95	34.97	27.79
			(600)	3.40	34.94	27.82
Station 2124; May 8; latitude 46°51′ N., longitude 46°18′ W.; depth 320 meters; dynamic height 970.815 meters						
0	4.55	34.28	0	4.55	34.28	27.17
26	4.69	34.32	25	4.70	34.32	27.19
51	4.56	34.34	50	4.55	34.34	27.22
77	4.07	34.42	75	4.10	34.42	27.34
103	4.28	34.64	100	4.25	34.61	27.47
154	4.04	34.77	150	4.05	34.76	27.61
206	4.23	34.91	200	4.20	34.90	27.71
309	3.68	34.94	300	3.70	34.94	27.79
Station 2125; May 8; latitude 46°51′ N., longitude 45°44′ W.; depth 224 meters; dynamic height 970.816 meters						
0	5.17	34.43	0	5.17	34.43	27.22
26	5.17	34.43	25	5.15	34.43	27.22
52	4.80	34.46	50	4.80	34.46	27.29
78	4.61	34.48	75	4.65	34.47	27.32
104	4.45	34.55	100	4.50	34.53	27.38
156	3.87	34.74	150	3.90	34.72	27.60
208	3.94	34.88	200	3.90	34.86	27.71
Station 2126; May 8; latitude 46°51′ N., longitude 44°58′ W.; depth 155 meters; dynamic height 970.830 meters						
0	5.36	34.46	0	5.36	34.46	27.23
21	5.19	34.45	25	5.15	34.45	27.24
47	5.08	34.46	50	5.05	34.46	27.26
73	4.64	34.46	75	4.60	34.46	27.31
98	4.47	34.47	100	4.45	34.48	27.34
145	4.01	34.60	(150)	3.95	34.61	27.50
Station 2127; May 8; latitude 46°54′ N., longitude 44°40′ W.; depth 130 meters; dynamic height 970.841 meters.						
0	5.27	34.42	0	5.27	34.42	27.21
26	4.87	34.43	25	4.85	34.43	27.26
52	4.69	34.44	50	4.70	34.44	27.28
79	4.37	34.44	75	4.40	34.44	27.32
105	4.27	34.50	100	4.25	34.48	27.36
Station 2128; May 8; latitude 46°45′ N., longitude 44°40′ W.; depth 167 meters; dynamic height 970.842 meters.						
0	4.96	34.36	0	4.96	34.36	27.20
26	4.66	34.37	25	4.70	34.37	27.23
52	4.25	34.42	50	4.30	34.41	27.31
77	4.08	34.55	75	4.05	34.54	27.43
103	3.98	34.63	100	4.00	34.62	27.51
155	3.91	34.72	150	3.90	34.71	27.59
Station 2129; May 8; latitude 46°38′ N., longitude 44°41′ W.; depth 224 meters; dynamic height 970.832 meters.						
0	5.18	34.39	0	5.18	34.39	27.19
26	4.65	34.42	25	4.65	34.42	27.28
52	4.06	34.50	50	4.10	34.49	27.39
78	3.87	34.60	75	3.85	34.59	27.49
103	3.79	34.67	100	3.80	34.66	27.56
155	3.77	34.82	150	3.75	34.81	27.68
207	3.80	34.84	200	3.80	34.84	27.70
Station 2130; May 8; latitude 46°31′ N., longitude 44°41′ W.; depth 622 meters; dynamic height 970.838 meters.						
0	5.13	34.38	0	5.13	34.38	27.18
26	4.60	34.39	25	4.60	34.39	27.25
52	4.06	34.44	50	4.10	34.43	27.34
78	4.06	34.52	75	4.05	34.51	27.41
104	3.94	34.58	100	3.95	34.57	27.47
156	3.71	34.74	150	3.70	34.72	27.62
208	3.75	34.84	200	3.75	34.83	27.69
312	3.77	34.90	300	3.80	34.89	27.74
417	3.76	34.92	400	3.75	34.90	27.75
619	3.57	34.95	600	3.60	34.95	27.81
Station 2131; May 8; latitude 46°26′ N., longitude 44°42′ W.; depth 1,866 meters; dynamic height 970.849 meters.						
0	5.54	34.40	0	5.54	34.40	27.15
26	5.04	34.43	25	5.05	34.43	27.24
51	4.66	34.44	50	4.65	34.44	27.29
77	4.38	34.46	75	4.35	34.46	27.34
102	4.24	34.51	100	4.25	34.50	27.38
153	3.92	34.63	150	3.95	34.62	27.51
205	3.76	34.81	200	3.75	34.80	27.67
307	3.79	34.89	300	3.80	34.89	27.74
408	3.77	34.92	400	3.75	34.92	27.77
608	3.72	34.96	600	3.75	34.96	27.80
805	3.54	34.95	800	3.55	34.95	27.81
1,008	3.43	34.94	1,000	3.45	34.94	27.81
1,416	3.33	34.94				

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1936—Continued

Station 2132; May 8; latitude 46°13′ N., longitude 44°48′ W.; depth 3,310 meters; dynamic height 970.955 meters.

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	7.42	34.19	0	7.42	34.19	26.74
26	9.66	34.93	25	9.65	34.91	26.96
52	9.77	35.00	50	9.75	34.99	27.00
78	9.51	35.00	75	9.55	35.00	27.05
104	9.11	35.02	100	9.20	35.02	27.12
156	8.16	34.98	150	8.30	34.98	27.23
207	7.15	34.98	200	7.25	34.98	27.38
311	5.30	34.93	300	5.45	34.93	27.58
401	5.01	35.00	400	5.05	35.00	27.69
600	4.37	35.01	600	4.35	35.01	27.78
798	3.94	35.00	800	3.95	35.00	27.81
1,000	3.61	34.97	1,000	3.60	34.97	27.83
1,405	3.49	34.96				

Station 2133; May 8–9; latitude 46°06′ N., longitude 45°23′ W.; depth 2,634 meters; dynamic height 970.969 meters.

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	9.53	34.65	0	9.53	34.65	26.77
23	9.44	34.66	25	9.45	34.66	26.80
46	9.04	34.79	50	9.05	34.83	26.99
69	9.79	35.05	75	9.75	35.04	27.04
92	9.45	35.00	100	9.25	34.99	27.09
138	8.28	34.93	150	7.90	34.88	27.21
183	6.83	34.78	200	6.65	34.80	27.33
275	5.47	34.86	300	5.15	34.87	27.58
255	6.08	34.92	400	4.40	34.90	27.68
397	4.40	34.90	600	4.00	34.95	27.77
549	3.95	34.93	800	4.10	35.00	27.80
711	4.12	35.00	1,000	3.70	34.98	27.82
1,064	3.66	34.97				

Station 2134; May 9; latitude 46°09′ N., longitude 46°02′ W.; depth 1,234 meters; dynamic height 970.921 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	5.03	33.86	0	5.03	33.86	26.79
23	6.66	34.34	25	6.70	34.35	26.97
46	6.85	34.44	50	6.80	34.43	27.01
68	6.45	34.40	75	6.35	34.40	27.05
91	6.18	34.41	100	6.05	34.46	27.14
137	5.56	34.69	150	5.40	34.71	27.42
183	5.17	34.76	200	5.05	34.78	27.51
274	4.57	34.88	300	4.40	34.88	27.66
306	4.32	34.88	400	4.05	34.90	27.72
470	3.89	34.92	600	3.80	34.94	27.78
641	3.75	34.95	800	3.60	34.94	27.80
827	3.57	34.94	1,000	3.45	34.92	27.80
973	3.46	34.92				

Station 2135; May 9; latitude 46°11′ N., longitude 46°27′ W.; depth 633 meters; dynamic height 970.857 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	3.23	33.54	0	3.23	33.54	26.72
26	2.80	33.76	25	2.80	33.76	26.94
51	2.69	33.90	50	2.70	33.89	27.04
77	2.98	34.26	75	2.95	34.24	27.30
102	2.98	34.50	100	3.00	34.48	27.49
153	3.58	34.72	150	3.55	34.71	27.62
205	3.78	34.83	200	3.75	34.82	27.69
307	4.27	34.96	300	4.25	34.96	27.75
408	3.93	34.96	400	3.95	34.96	27.78
610	3.55	34.94	600	3.55	34.94	27.80

Station, 2136; May 9; latitude 46°14 N., longitude 46°51′ W.; depth 1,262 meters; dynamic height 970.844 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	2.50	33.64	0	2.50	33.64	26.86
26	2.38	33.86	25	2.40	33.86	27.05
51	2.72	34.17	50	2.70	34.16	27.26
77	2.90	34.30	75	2.90	34.29	27.35
102	3.14	34.52	100	3.15	34.49	27.48
153	3.37	34.78	150	3.35	34.77	27.69
205	3.50	34.82	200	3.50	34.82	27.72
307	3.70	34.89	300	3.70	34.89	27.75
404	3.82	34.92	400	3.80	34.92	27.77
605	3.71	34.94	600	3.70	34.94	27.79
806	3.53	34.94	800	3.55	34.94	27.80
1,012	3.40	34.92	1,000	3.40	34.92	27.81

Station, 2137; May 9; latitude 46°16′ N., longitude 47°17′ W.; depth 622 meters; dynamic height 970.896 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	0.84	32.85	0	0.84	32.85	26.36
26	.82	33.46	25	.80	33.44	26.82
51	1.58	33.75	50	1.55	33.74	27.01
77	1.82	34.00	75	1.80	33.98	27.19
103	1.86	34.26	100	1.85	34.22	27.38
154	2.84	34.56	150	2.80	34.54	27.55
206	3.15	34.70	200	3.10	34.68	27.64
309	3.56	34.82	300	3.55	34.81	27.70
298	3.52	34.80	400	3.70	34.87	27.74
482	3.71	34.90	(600)	3.70	34.92	27.78

Station 2138; May 9; latitude 46°18′ N., longitude 47°43′ W.; depth 165 meters; dynamic height 971.020 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	0.65	32.69	0	0.65	32.69	26.23
26	.12	32.72	25	.15	32.72	26.28
53	−.02	32.86	50	.00	32.83	26.38
79	.15	33.19	75	.15	33.14	26.62
105	−.17	33.41	100	−.15	33.38	26.83
158	.05	33.52	150	.00	33.51	26.93

Station 2139; May 9; latitude 46°21′ N., longitude 48°05′ W.; depth 107 meters; dynamic height 971.008 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	2.00	33.02	0	2.00	33.02	26.41
26	2.11	33.22	25	2.10	33.22	26.56
52	1.28	33.26	50	1.35	33.25	26.64
77	.88	33.31	75	.90	33.30	26.70
97	.87	33.30	100	.90	33.31	26.71

Station 2140; May 9; latitude 46°23′ N., longitude 48°36′ W.; depth 88 meters; dynamic height 971.008 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	2.79	33.16	0	2.79	33.16	26.46
26	2.72	33.19	25	2.75	33.19	26.49
51	1.57	33.25	50	1.60	33.24	26.62
77	.78	33.33	75	.80	33.32	26.73

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1936—Continued

Station 2141; May 10; latitude 46°25′ N., longitude 48°55′ W.; depth 68 meters; dynamic height 971.017 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	3.01	33.28	0	3.01	33.28	26.54
26	2.88	33.28	25	2.90	33.28	26.55
53	2.45	33.31	50	2.50	33.31	26.60

Station 2142; May 10; latitude 46°13′ N., longitude 48°38′W.; depth 88 meters; dynamic height 971.029 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	2.77	33.15	0	2.77	33.15	26.46
26	2.74	33.19	25	2.75	33.19	26.49
51	1.59	33.24	50	1.65	33.24	26.61
77	.79	33.34	75	.85	33.33	26.73

Station 2143; May 10; latitude 46°02′ N., longitude 48°18′ W.; depth 110 meters; dynamic height 971.046 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	0.82	32.72	0	0.82	32.72	26.25
20	.77	32.75	25	.70	32.76	26.28
45	.02	32.80	50	−.05	32.83	26.38
70	−.34	32.98	75	−.35	33.03	26.55
95	.01	33.30	(100)	.10	33.36	26.80

Station 2144; May 10; latitude 45°58′ N., longitude 48°12′ W.; depth 165 meters; dynamic height 971.036 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	0.50	32.68	0	0.50	32.68	26.24
18	.48	32.70	25	.35	32.73	26.28
42	−.06	32.84	50	−.05	32.91	26.44
66	−.02	33.15	75	−.05	33.30	26.75
90	−.09	33.46	100	−.05	33.47	26.90
138	.02	33.48	(150)	.10	33.48	26.90

Station 2145; May 10; latitude 45°50′ N., longitude 47°57′ W.; depth 622 meters; dynamic height 970.970 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	0.56	32.82	0	0.56	32.82	26.34
22	.54	32.82	25	.55	32.82	26.34
44	−.14	33.03	50	−.25	33.09	26.59
66	−.43	33.26	75	−.25	33.37	26.82
88	.05	33.48	100	.45	33.63	26.99
132	1.42	34.04	150	1.95	34.23	27.38
176	2.53	34.46	200	2.65	34.49	27.53
264	2.83	34.58	300	3.00	34.64	27.62
253	2.81	34.56	(400)	3.60	34.81	27.70
367	3.48	34.76	(600)	3.80	34.92	27.77

Station 2146; May 10; latitude 45°42′ N., longitude 47°54′ W.; depth 1,097 meters; dynamic height 970.895 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	1.04	33.07	0	1.04	33.07	26.52
25	.47	33.36	25	.47	33.36	26.77
50	1.24	33.63	50	1.24	33.63	26.94
75	1.24	33.88	75	1.24	33.88	27.14
100	2.26	34.12	100	2.26	34.12	27.27
150	3.11	34.55	150	3.11	34.55	27.54
200	3.12	34.72	200	3.12	34.72	27.68
300	3.51	34.84	300	3.51	34.84	27.73
332	3.57	34.85	400	3.65	34.88	27.74
505	3.80	34.92	600	3.85	34.95	27.78
684	3.84	34.96	800	3.80	34.96	27.80
907	3.70	34.96	(1,000)	3.65	34.95	27.80

Station 2147; May 10; latitude 45°32′ N., longitude 47°45′ W.; depth 1,536 meters; dynamic height 970.869 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	2.49	33.44	0	2.49	33.44	26.70
26	2.24	33.50	25	2.25	33.50	26.78
52	2.51	34.16	50	2.45	34.09	27.22
77	3.19	34.46	75	3.10	34.44	27.45
103	4.51	34.74	100	4.35	34.69	27.52
155	5.04	34.89	150	5.05	34.88	27.59
207	4.84	34.94	200	4.90	34.93	27.65
310	4.52	34.98	300	4.55	34.98	27.73
414	4.22	34.98	400	4.30	34.98	27.75
618	3.70	34.94	600	3.75	34.94	27.78
820	3.60	34.94	800	3.60	34.94	27.80
1,025	3.40	34.94	1,000	3.45	34.94	27.81
1,437	3.32	34.94				

Station 2148; May 10; latitude 45°21′ N., longitude 47°18′ W.; depth 2,451 meters; dynamic height 970.914 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	3.61	33.38	0	3.61	33.38	26.56
26	3.56	33.40	25	3.55	33.40	26.58
51	6.74	34.29	50	6.70	34.28	26.91
77	3.37	33.98	75	3.40	33.98	27.05
103	4.13	34.34	100	4.15	34.29	27.22
154	3.93	34.58	150	3.95	34.56	27.46
206	4.21	34.76	200	4.20	34.74	27.58
309	4.08	34.87	300	4.10	34.86	27.69
414	4.17	34.95	400	4.15	34.94	27.74
617	3.86	34.96	600	3.90	34.96	27.79
818	3.61	34.96	800	3.65	34.96	27.81
1,023	3.49	34.95	1,000	3.50	34.95	27.82
1,435	3.30	34.93				

Station 2149; May 10; latitude 45°22′ N., longitude 46°39′ W.; depth 3,045 meters; dynamic height 970.939 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	7.20	34.14	0	7.20	34.14	26.73
26	8.12	34.38	25	8.10	34.38	26.79
52	8.50	34.63	50	8.50	34.61	26.91
78	8.17	34.72	75	8.20	34.71	27.04
104	7.50	34.82	100	7.70	34.81	27.19
156	5.66	34.64	150	5.80	34.65	27.32
207	5.08	34.72	200	5.10	34.71	27.46
311	4.65	34.90	300	4.70	34.89	27.64
404	4.40	34.95	400	4.40	34.95	27.72
603	3.89	34.95	600	3.90	34.95	27.78
800	3.65	34.94	800	3.65	34.94	27.79
1,003	3.48	34.94	1,000	3.50	34.94	27.81
1,411	3.33	34.935				

Station 2150; May 11; latitude 45°22′ N., longitude 45°51′ W.; depth 3,658 meters; dynamic height 970.909 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	5.36	33.82	0	5.36	33.82	26.72
26	5.54	33.85	25	5.55	33.85	26.72
52	6.11	34.28	50	6.05	34.23	26.96
77	6.76	34.66	75	6.75	34.65	27.20
103	6.73	34.76	100	6.75	34.75	27.28
155	6.06	34.85	150	6.15	34.85	27.44
207	4.72	34.79	200	4.75	34.79	27.56
310	4.67	34.94	300	4.65	34.93	27.68
403	4.69	35.01	400	4.70	35.01	27.74
604	4.14	35.00	600	4.15	35.00	27.79
803	3.79	34.97	800	3.80	34.97	27.81
1,006	3.54	34.96	1,000	3.55	34.96	27.82
1,416	3.31	34.935				

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1936—Continued

Station 2151; May 11; latitude 44°56′ N., longitude 45°59′ W.; depth 3,704 meters; dynamic height 971.021 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	10.80	34.72	0	10.80	34.72	26.61
25	10.61	34.69	25	10.61	34.69	26.62
51	11.44	35.205	50	11.45	35.20	26.88
76	11.42	35.26	75	11.40	35.26	26.93
102	11.23	35.24	100	11.30	35.25	26.93
153	8.38	34.82	150	8.60	34.85	27.08
204	6.59	34.66	200	6.65	34.76	27.30
306	5.52	34.78	300	5.55	34.78	27.45
393	5.08	34.89	400	5.05	34.89	27.60
588	4.29	34.96	600	4.25	34.96	27.75
782	4.00	34.97	800	4.00	34.97	27.79
980	3.67	34.96	1,000	3.65	34.96	27.81
1,378	3.33	34.94				

Station 2152; May 11; latitude 44°21′ N., longitude 46°05′ W.; depth 3,887 meters; dynamic height 971.262 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	15.70	35.73	0	15.70	35.73	26.40
21	15.77	35.76	25	15.80	35.79	26.41
42	15.91	35.98	50	15.95	36.00	26.55
62	15.97	36.02	75	15.75	36.01	26.60
83	15.60	36.00	100	15.60	36.06	26.67
125	15.62	36.16	150	14.70	35.95	26.78
166	14.00	35.79	200	12.65	35.54	26.90
249	12.06	35.40	300	11.60	35.40	26.99
228	11.98	35.42	400	9.10	35.18	27.26
321	11.27	35.40	600	6.85	35.13	27.56
413	8.83	35.16	(800)	4.60	35.00	27.74
521	7.82	35.17	(1,000)	3.90	34.95	27.78
756	4.87	35.02				

Station 2153; May 11; latitude 44°27′ N., longitude 46°38′ W.; depth 3,914 meters; dynamic height 971.180 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	14.94	35.55	0	14.94	35.55	26.43
29	15.02	35.64	25	15.00	35.64	26.48
59	14.39	35.63	50	14.70	35.63	26.54
88	13.31	35.55	75	13.70	35.58	26.72
116	13.16	35.60	100	13.20	35.57	26.81
175	11.96	35.40	150	12.40	35.48	26.90
233	11.51	35.42	200	11.75	35.41	26.98
349	9.36	35.23	300	10.35	35.31	27.15
464	7.46	35.12	400	8.45	35.17	27.36
739	4.60	35.02	600	5.65	35.05	27.66
1,044	4.08	35.02	800	4.50	35.02	27.77
1,308	3.65	34.98	1,000	4.15	35.02	27.81
1,839	3.32	34.95				

Station 2154; May 12; latitude 44°36′ N., longitude 47°24′ W.; depth 3,823 meters; dynamic height 971.006 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	7.89	33.59	0	7.89	33.59	26.20
26	7.31	33.82	25	7.35	33.81	26.46
51	5.66	33.99	50	5.65	33.99	26.82
77	5.78	34.22	75	5.75	34.21	26.98
103	5.70	34.28	100	5.70	34.27	27.04
135	6.80	34.53	150	7.15	34.65	27.14
180	7.47	34.84	200	7.55	34.91	27.29
270	7.22	35.01	300	6.45	34.97	27.49
358	5.10	34.86	400	4.65	34.88	27.64
529	4.10	35.00	600	4.05	35.00	27.80
1,273	3.50	34.95	800	3.85	34.98	27.80
			1,000	3.70	34.97	27.82

Station 2155; May 12; latitude 44°45′ N., longitude 48°08′ W.; depth 2,707 meters; dynamic height 970.897 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	5.61	33.52	0	5.61	33.52	26.46
26	5.59	33.66	25	5.60	33.65	26.56
51	5.20	34.28	50	5.20	34.25	27.08
77	5.02	34.47	75	5.00	34.46	27.27
103	5.29	34.65	100	5.30	34.63	27.36
154	4.66	34.74	150	4.75	34.73	27.51
206	4.01	34.76	200	4.05	34.76	27.61
309	5.00	35.03	300	5.00	35.02	27.72
413	4.33	34.98	400	4.40	34.99	27.75
616	3.96	34.98	600	4.00	34.98	27.79
817	3.52	34.94	800	3.55	34.94	27.80
1,022	3.45	34.94	1,000	3.45	34.94	27.81
1,433	3.30	34.94				

Station 2156; May 12; latitude 44°51′ N., longitude 48°40′ W.; depth 1,536 meters; dynamic height 970.918 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	1.52	32.90	0	1.52	32.90	26.34
24	.53	33.14	25	.55	33.15	26.60
48	.77	33.57	50	.80	33.60	26.95
72	1.06	33.74	75	1.10	33.75	27.05
96	3.16	34.19	100	3.15	34.20	27.25
144	2.37	34.31	150	2.45	34.34	27.42
191	2.92	34.64	200	3.00	34.68	27.65
287	3.43	34.81	300	3.45	34.81	27.71
320	3.45	34.82	400	3.70	34.87	27.74
482	3.84	34.92	600	3.85	34.94	27.77
647	3.86	34.94	800	3.75	34.94	27.78
823	3.73	34.94	1,000	3.60	34.94	27.80
1,193	3.48	34.94				

Station 2157; May 12; latitude 44°54′ N., longitude 48°55° W.; depth 622 meters; dynamic height 971.060 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	1.41	32.66	0	1.41	32.66	26.16
26	.08	32.71	25	.10	32.71	26.28
51	−.94	32.94	50	−.95	32.93	26.49
77	−.25	33.30	75	−.25	33.29	26.75
103	−.17	33.36	100	−.15	33.35	26.80
154	−.09	33.45	150	−.10	33.44	26.87
205	1.00	33.92	200	90	33.86	27.16
308	2.41	34.44	300	2.35	34.41	27.49
401	3.09	34.69	400	3.10	34.68	27.64
597	3.51	34.85	600	3.50	34.85	27.74

Station 2158; May 12; latitude 44°56′ N., longitude 49°00′ W.; depth 199 meters; dynamic height 971.136 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	1.99	32.62	0	1.99	32.62	26.09
26	.13	32.71	25	.20	32.71	26.27
51	−.11	33.02	50	−.10	33.01	26.53
77	0.00	33.10	75	0.00	33.10	26.59
103	.10	33.13	100	.10	33.13	26.62
154	−.16	33.28	150	−.15	33.27	26.74
185	−.03	33.36	(200)	.05	33.39	26.83

Station 2159; May 12; latitude 44°57′ N., longitude 49°09′ W.; depth 88 meters; dynamic height 971.154 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	1.79	32.70	0	1.79	32.70	26.16
26	.87	32.78	25	.90	32.78	26.29
52	.53	32.84	50	.55	32.81	26.34
78	.27	33.00	75	.30	32.98	26.49

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1936—Continued

Station 2160; May 12; latitude 45°02′ N., longitude 49°33′ W.; depth 64 meters; dynamic height 971.150 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	4.21	32.86	0	4.21	32.86	26.09
22	2.04	32.92	25	2.00	32.93	26.34
47	1.19	33.01	50	1.15	33.03	26.48

Station 2161; May 12; latitude 44°11′ N., longitude 49°36′ W.; depth 50 meters; dynamic height 971.127 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	4.77	33.21	0	4.77	33.21	26.31
13	4.36	33.26	25	4.25	33.27	26.40
40	4.16	33.27	(50)	4.10	33.28	26.43

Station 2162; May 13; latitude 44°05′ N., longitude 49°12′ W.; depth 88 meters; dynamic height 971.130 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	1.03	32.71	0	1.03	32.71	26.22
26	.48	32.75	25	.50	32.75	26.29
51	.14	32.90	50	.15	32.90	26.43
77	.03	32.98	75	.05	32.98	26.50

Station 2163; May 13; latitude 44°04′ N., longitude 49°08′ W.; depth 220 meters; dynamic height 971.126 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	1.08	32.67	0	1.08	32.67	26.19
8	.83	32.67	25	0.00	32.69	26.26
30	−.20	32.71	50	−.25	33.02	26.54
52	−.27	33.06	75	−.20	33.15	26.64
74	−.20	33.15	100	−.20	33.16	26.65
118	−.22	33.16	150	−.15	33.21	26.70
162	−.16	33.24	(200)	−.10	33.31	26.76

Station 2164; May 13; latitude 44°01′ N., longitude 49°00′ W.; depth 649 meters; dynamic height 971.082 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	0.76	32.64	0	0.76	32.64	26.19
25	−.07	32.70	25	−.07	32.70	26.27
51	.07	33.16	50	.05	33.15	26.64
76	−.07	33.17	75	−.05	33.17	26.65
102	−.13	33.33	100	−.10	33.31	26.76
153	.28	33.57	150	.25	33.55	26.95
204	1.48	34.07	200	1.35	34.03	27.26
306	2.81	34.52	300	2.80	34.51	27.53
406	3.03	34.62	400	3.05	34.61	27.59
607	3.44	34.76	600	3.45	34.75	27.66

Station 2165; May 13; latitude 43°58′ N., longitude 48°50′ W.; depth 1,509 meters; dynamic height 971.005 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	1.20	32.70	0	1.20	32.70	26.21
25	.34	32.84	25	.34	32.84	26.37
51	−.48	33.09	50	−.50	33.09	26.60
76	−.28	33.32	75	−.30	33.31	26.77
102	1.20	33.71	100	1.10	33.67	26.99
153	1.72	34.13	150	1.70	34.10	27.29
203	2.37	34.38	200	2.35	34.37	27.46
305	3.02	34.63	300	3.00	34.62	27.61
396	3.24	34.70	400	3.25	34.70	27.64
591	4.17	34.93	600	4.15	34.93	27.73
784	3.73	34.90	800	3.70	34.90	27.76
980	3.57	34.90	1,000	3.55	34.90	27.77
1,371	3.47	34.87				

Station 2166; May 13; latitude 43°52′ N., longitude 48°20′ W.; depth 3,365 meters; dynamic height 970.969 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	8.23	34.09	0	8.23	34.09	26.54
25	8.16	34.11	25	8.16	34.11	26.57
50	6.91	34.28	50	6.91	34.28	26.88
76	6.49	34.42	75	6.50	34.41	27.04
101	5.96	34.52	100	5.95	34.51	27.19
151	5.78	34.73	150	5.80	34.73	27.38
200	5.25	34.77	200	5.25	34.77	27.49
302	4.95	34.92	300	4.95	34.92	27.64
394	4.85	34.96	400	4.85	34.96	27.68
591	4.18	34.94	600	4.15	34.94	27.74
788	3.90	34.94	800	3.90	34.94	27.77
988	3.60	34.94	1,000	3.60	34.94	27.80
1,390	3.32	34.89				

Station 2167; May 13; latitude 43°44′ N., longitude 47°45′ W.; depth 3,941 meters; dynamic height 970.925 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	8.13	33.74	0	8.13	33.74	26.29
26	6.56	34.06	25	6.55	34.06	26.76
52	5.94	34.11	50	6.00	34.10	26.86
77	5.32	34.43	75	5.35	34.40	27.18
103	5.43	34.61	100	5.40	34.59	27.32
155	5.34	34.76	150	5.35	34.75	27.46
207	5.39	34.90	200	5.40	34.89	27.56
310	4.74	34.94	300	4.80	34.93	27.66
407	4.78	35.01	400	4.80	35.01	27.73
610	4.13	34.99	600	4.15	34.99	27.78
811	3.92	34.98	800	3.95	34.98	27.79
1,014	3.71	34.97	1,000	3.75	34.97	27.81
1,420	3.40	34.97				

Station 2168; May 13; latitude 43°40′ N., longitude 47°06′ W.; depth 4,289 meters; dynamic height 970.935 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	8.94	33.98	0	8.94	33.98	26.35
26	8.44	34.15	25	8.50	34.15	26.55
52	6.43	34.36	50	6.75	34.34	26.95
78	5.92	34.56	75	5.95	34.56	27.10
104	4.81	34.49	100	4.85	34.49	27.31
156	5.14	34.67	150	5.10	34.65	27.41
208	5.54	34.86	200	5.50	34.85	27.52
312	4.28	34.84	300	4.35	34.84	27.64
412	4.82	35.02	400	4.85	35.01	27.72
614	4.38	35.015	600	4.40	35.02	27.78
813	3.84	34.97	800	3.90	34.98	27.80
1,018	3.58	34.96	1,000	3.60	34.96	27.82
1,431	3.32	34.945				

Station 2169; May 13; latitude 43°36′ N., longitude 46°26′ W.; depth 4,536 meters; dynamic height 971.055 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	6.07	32.97	0	6.07	32.97	25.96
26	11.55	34.71	25	11.55	34.68	26.44
51	11.15	34.98	50	11.20	34.98	26.74
77	8.92	34.63	75	9.10	34.66	26.86
103	7.23	34.47	100	7.35	34.48	26.98
154	7.87	34.74	150	7.85	34.72	27.10
205	7.08	34.75	200	7.25	34.75	27.21
308	3.61	34.44	300	3.70	34.44	27.40
375	5.07	34.82	400	5.10	34.87	27.58
557	4.93	35.02	600	4.75	35.02	27.74
736	4.26	35.00	800	4.10	35.00	27.80
927	3.90	34.99	1,000	3.85	34.99	27.81
1,317	3.57	34.98				

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1936—Continued

Station 2170; May 14; latitude 43°12′ N., longitude 46°39′ W.; depth 4,198 meters; dynamic height 971.084 meters.

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	11.19	34.13	0	11.19	34.13	26.08
26	12.12	34.90	25	12.10	34.88	26.50
52	11.49	35.10	50	11.55	35.08	26.75
78	11.89	35.34	75	11.85	35.33	26.89
104	11.21	35.21	100	11.30	35.21	26.91
156	10.56	35.20	150	10.65	35.20	27.01
208	9.77	35.20	200	9.90	35.20	27.14
312	3.67	34.38	300	4.00	34.40	27.33
304	3.77	34.38	400	4.15	34.65	27.51
443	4.38	34.80	600	4.75	35.01	27.73
573	4.80	35.01	800	4.10	34.99	27.79
728	4.33	34.99	1,000	3.90	34.99	27.81
1,051	3.87	34.99				

Station 2171; May 14; latitude 42°47′ N., longitude 46°52′ W.; depth 4,070 meters; dynamic height 971.184 meters.

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	16.48	35.55	0	16.48	35.55	26.08
29	15.04	35.56	25	15.25	35.56	26.37
56	13.95	35.56	50	14.10	35.56	26.62
85	13.73	35.61	75	13.75	35.59	26.71
113	13.81	35.71	100	13.80	35.67	26.76
170	11.92	35.38	150	12.60	35.49	26.87
227	10.91	35.24	200	11.35	35.28	26.94
340	9.48	35.27	300	10.05	35.26	27.16
494	6.30	34.99	400	8.05	35.14	27.39
732	4.46	34.99	600	5.15	34.99	27.67
961	4.06	35.00	800	4.35	34.99	27.76
1,203	3.66	34.97	1,000	4.00	35.00	27.81
1,688	3.39	34.95				

Station 2172; May 14; latitude 42°54′ N., longitude 47°44′ W.; depth 3,738 meters; dynamic height 970.920 meters.

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	8.17	33.53	0	8.17	33.53	26.12
26	6.18	33.57	25	6.20	33.57	26.42
52	5.37	34.24	50	5.40	34.16	26.98
78	6.29	34.62	75	6.25	34.62	27.24
104	4.58	34.48	100	4.70	34.49	27.32
156	5.16	34.74	150	5.15	34.73	27.46
207	4.79	34.82	200	4.80	34.81	27.57
311	4.50	34.95	300	4.50	34.94	27.70
409	4.51	34.97	400	4.50	34.97	27.73
610	4.01	34.97	600	4.05	34.97	27.78
809	3.64	34.95	800	3.65	34.95	27.80
1,013	3.44	34.93	1,000	3.45	34.93	27.80
1,422	3.31	34.94				

Station 2173; May 14; latitude 43°06′ N., longitude 48°25′ W.; depth 3,081 meters; dynamic height 970.907 meters.

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	8.37	33.90	0	8.37	33.90	26.38
26	6.06	33.95	25	6.05	33.95	26.74
52	6.44	34,34	50	6.45	34.30	26.96
77	4.74	34.45	75	4.75	34.44	27.28
103	5.08	34.61	100	5.05	34.59	27.36
155	5.23	34.79	150	5.25	34.78	27.49
207	4.74	34.84	200	4.75	34.83	27.59
310	4.75	34.96	300	4.75	34.95	27.68
416	4.47	34.98	400	4.50	34.98	27.73
620	3.95	34.97	600	4.00	34.97	27.79
823	3.53	34.93	800	3.55	34.93	27.79
1,029	3.51	34.94	1,000	3.50	34.94	27.81
1,442	3.32	34.93				

Station 2174; May 15; latitude 43°18′ N., longitude 49°04′ W.; depth 1,472 meters; dynamic height 970.892 meters.

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	3.45	33.02	0	3.45	33.02	26.28
25	1.58	33.40	25	1.58	33.40	26.74
51	1.31	33.74	50	1.30	33.72	27.02
76	1.85	34.23	75	1.85	34.22	27.38
101	1.86	34.27	100	1.85	34.26	27.41
152	2.93	34.56	150	2.90	34.53	27.54
203	3.43	34.70	200	3.40	34.69	27.62
304	3.76	34.87	300	3.75	34.86	27.72
380	3.91	34.90	400	3.90	34.90	27.74
572	3.79	34.92	600	3.75	34.92	27.77
765	3.64	34.94	800	3.60	34.94	27.80
963	3.45	34.92	1,000	3.45	34.92	27.80
1,369	3.35	34.93				

Station 2175; May 15; latitude 43°15′ N, longitude 50°05′ W.; depth 68 meters; dynamic height 971.072 meters.

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	5.52	32.90	0	5.52	32.90	25.97
25	3.34	32.96	25	3.34	32.96	26.25
51	1.17	33.08	50	1.25	33.07	26.50

Station 2176; May 15; latitude 43°01′ N., longitude 50°05′ W.; depth 82 meters; dynamic height 971.064 meters.

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	3.32	32.94	0	3.32	32.94	26.24
20	2.54	32.96	25	2.10	32.99	26.38
45	.42	33.10	50	.40	33.11	26.58
76	.28	33.14	75	.30	33.14	26.62

Station 2177; May 15; latitude 42°48′ N., longitude 50°04′ W.; depth 622 meters; dynamic height 970.999 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	1.82	32.74	0	1.82	32.74	26.20
26	.08	33.06	25	.10	33.05	26.56
51	.31	33.48	50	.30	33.46	26.87
77	.67	33.76	75	.65	33.74	27.07
102	1.25	33.98	100	1.15	33.95	27.21
153	1.83	34.21	150	1.80	34.20	27.37
205	2.04	34.29	200	2.00	34.28	27.41
307	2.60	34.48	300	2.60	34.47	27.52
399	2.93	34.62	400	2.95	34.62	27.61
596	3.62	34.84	600	3.65	34.84	27.71

Station 2178; May 15; latitude 42°37′ N., longitude 50°04′ W.; depth 2,103 meters; dynamic height 970.898 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	3.70	33.02	0	3.70	33.02	26.26
25	1.54	33.38	25	1.54	33.38	26.73
49	1.95	33.84	50	1.95	33.87	27.09
74	2.42	34.17	75	2.40	34.17	27.30
98	2.30	34.30	100	2.30	34.31	27.42
147	2.53	34.51	150	2.55	34.52	27.57
197	2.78	34.61	200	2.80	34.62	27.62
295	3.41	34.80	300	3.45	34.81	27.71
359	3.55	34.84	400	3.65	34.86	27.73
543	3.90	34.935	600	3.85	34.94	27.77
730	3.78	34.945	800	3.75	34.94	27.78
923	3.65	34.945	1,000	3.65	34.94	27.79
1,321	3.47	34.94				

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1936—Continued

Station 2179; May 15; latitude 42°18′ N., longitude 50°05′ W.; depth 3,008 meters; dynamic height 970.917 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	7.76	33.25	0	7.76	33.25	25.96
25	4.57	33.22	25	4.57	33.22	26.33
51	2.12	33.71	50	2.25	33.70	26.93
76	2.79	34.14	75	2.75	34.13	27.23
102	3.36	34.35	100	3.30	34.33	27.34
153	4.80	34.73	150	4.70	34.72	27.51
204	5.08	34.88	200	5.05	34.87	27.59
306	4.64	34.95	300	4.65	34.95	27.70
396	4.73	35.005	400	4.75	35.00	27.72
592	4.27	35.02	600	4.25	35.02	27.80
785	3.96	35.005	800	3.95	35.00	27.81
986	3.76	34.995	1,000	3.75	35.00	27.83
1,395	3.50	34.98				

Station 2180; May 15; latitude 42°00′ N., longitude 50°08′ W.; depth 3,365 meters; dynamic height 970.909 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	7.33	33.08	0	7.33	33.08	25.88
26	4.47	33.47	25	4.50	33.45	26.52
51	5.07	34.20	50	5.05	34.16	27.03
77	5.34	34.44	75	5.35	34.44	27.21
102	4.24	34.46	100	4.35	34.45	27.33
153	3.29	34.54	150	3.30	34.53	27.50
205	3.50	34.69	200	3.45	34.67	27.60
307	4.67	34.96	300	4.65	34.95	27.70
384	*4.65	35.01	400	4.60	35.01	27.75
578	4.32	35.02	600	4.30	35.02	27.79
772	4.00	35.02	800	4.00	35.01	27.82
970	3.75	34.99	1,000	3.70	34.98	27.82
1,370	3.38	34.945				

Station 2181; May 16; latitude 41°37′ N., longitude 49°20′ W.; depth 2,853 meters; dynamic height 971.123 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	11.00	33.67	0	11.00	33.67	25.77
25	11.44	34.82	25	11.44	34.82	26.58
49	12.70	35.42	50	12.70	35.43	26.80
74	12.59	35.48	75	12.55	35.48	26.87
99	11.91	35.36	100	11.90	35.35	26.90
148	9.97	35.04	150	9.75	35.01	27.02
197	6.57	34.46	200	6.55	34.46	27.08
296	6.37	34.66	300	6.30	34.66	27.27
362	4.79	34.52	400	4.90	34.63	27.41
548	5.33	35.00	600	5.15	35.01	27.69
737	4.59	35.01	800	4.40	35.01	27.77
929	3.98	34.99	1,000	3.80	34.98	27.81
1,324	3.47	34.96				

Station 2182; May 16; latitude 41°15′ N., longitude 48°34′ W.; depth 3,319 meters; dynamic height 971.096 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	11.24	33.71	0	11.24	33.71	25.75
25	9.09	34.44	25	9.09	34.44	26.68
51	10.74	35.05	50	10.70	35.04	26.88
76	10.85	35.13	75	10.85	35.13	26.92
102	10.78	35.14	100	10.80	35.14	26.94
153	10.80	35.22	150	10.80	35.22	27.00
204	7.72	34.74	200	7.90	34.77	27.13
306	8.63	35.15	300	8.60	35.15	27.32
414	6.37	35.00	400	6.60	35.01	27.50
618	4.41	34.94	600	4.45	34.94	27.71
821	4.18	34.98	800	4.20	34.97	27.77
1,024	4.01	35.00	1,000	4.05	35.00	27.80
1,430	3.54	34.96				

Station 2183; May 16; latitude 41°00′ N., longitude 47°39′ W.; depth 3,383 meters; dynamic height 971.203 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	18.45	35.40	0	18.45	35.40	25.48
25	15.66	35.72	25	15.66	35.72	26.40
50	14.56	35.55	50	14.56	35.55	26.51
75	12.54	35.16	75	12.54	35.16	26.62
100	13.82	35.64	100	13.82	35.64	26.74
150	13.04	35.58	150	13.04	35.58	26.86
200	11.50	35.30	200	11.50	35.30	26.94
300	10.51	35.34	300	10.51	35.34	27.15
313	10.30	35.34	400	8.55	35.21	27.37
474	7.23	35.09	600	5.75	35.08	27.66
639	5.41	35.08	800	4.60	35.04	27.77
813	4.54	35.04	1,000	4.10	35.01	27.81
1,177	3.84	35.00				

Station 2184; May 16–17; latitude 41°45′ N., longitude 47°14′ W.; depth 4,115 meters; dynamic height 971.239 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	17.95	36.00	0	17.95	36.00	26.07
26	17.72	35.96	25	17.75	35.96	26.08
51	13.99	35.35	50	14.00	35.36	26.49
77	13.71	35.51	75	13.70	35.51	26.66
103	13.37	35.52	100	13.40	35.52	26.73
153	12.55	35.48	150	12.60	35.49	26.87
204	11.24	35.25	200	11.30	35.26	26.94
307	10.59	35.37	300	10.65	35.37	27.15
429	7.63	35.02	400	8.40	35.09	27.30
649	5.69	35.01	600	5.95	35.01	27.59
971	4.51	35.07	800	5.10	35.04	27.71
1,110	4.02	35.02	1,000	4.40	35.06	27.81
1,570	3.51	34.975				

Station 2185; May 17; latitude 42°10′ N., longitude 47°47′ W.; depth 3,676 meters; dynamic height 971.082 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	11.76	33.55	0	11.76	33.55	25.53
25	8.32	34.16	25	8.32	34.16	26.59
48	10.52	34.93	50	10.65	34.97	26.84
73	11.06	35.15	75	11.05	35.16	26.90
97	10.92	35.17	100	10.85	35.16	26.95
146	9.91	35.05	150	9.90	35.06	27.04
195	9.95	35.18	200	9.80	35.18	27.14
292	7.42	34.95	300	7.35	34.95	27.35
244	8.47	35.08	400	6.60	35.08	27.55
386	6.77	35.09	600	4.90	35.03	27.73
501	5.19	35.00	800	4.30	35.02	27.79
646	4.78	35.04	(1,000)	3.75	34.97	27.81
961	3.81	34.98				

Station 2186; May 17; latitude 42°36′ N., longitude 48°30′ W.; depth 3,182 meters; dynamic height 970.920 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	8.38	33.25	0	8.38	33.25	25.86
26	5.69	33.50	25	5.75	33.49	26.41
51	2.65	33.97	50	2.70	33.95	27.09
77	3.23	34.20	75	3.20	34.19	27.24
103	3.20	34.32	100	3.20	34.31	27.34
154	3.62	34.54	150	3.60	34.53	27.47
205	3.49	34.66	200	3.50	34.65	27.58
308	4.43	34.90	300	4.40	34.89	27.67
389	4.04	34.90	400	4.05	34.90	27.72
611	3.98	34.98	600	4.00	34.98	27.79
785	3.76	34.97	800	3.75	34.97	27.81
984	3.48	34.95	1,000	3.50	34.95	27.82
1,385	3.29	34.945				

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1936—Continued

Station 2187; May 17; latitude 42°31′ N., longitude 49°11′ W.; depth 2,726 meters; dynamic height 970.893 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	6.01	33.15	0	6.01	33.15	26.12
26	5.20	33.30	25	5.25	33.30	26.31
52	2.54	33.88	50	2.75	33.83	26.99
77	3.24	34.28	75	3.25	34.26	27.29
103	3.19	34.48	100	3.20	34.45	27.45
155	4.59	34.79	150	4.50	34.78	27.57
207	4.27	34.83	200	4.30	34.83	27.64
310	4.25	34.91	300	4.25	34.90	27.70
415	4.14	34.96	400	4.15	34.96	27.76
620	3.74	34.96	600	3.80	34.96	27.80
823	3.51	34.95	800	3.55	34.95	27.81
1,028	3.40	34.95	1,000	3.40	34.95	27.83
1,436	3.32	34.94				

Station 2188; June 2; latitude 43°23′ N., longitude 49°33′ W.; depth 82 meters; dynamic height 971.088 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	6.20	32.93	0	6.20	32.93	25.91
26	4.84	32.98	25	4.90	32.98	26.11
51	1.45	33.01	50	1.75	33.01	26.43
72	1.08	33.10	75	1.05	33.11	26.55

Station 2189; June 2; latitude 43°22′ N., longitude 49°31′ W.; depth 229 meters; dynamic height 971.089 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	6.64	33.02	0	6.64	33.02	25.93
22	5.39	33.01	25	5.15	33.01	26.11
45	2.35	33.005	50	2.00	33.01	26.41
67	1.18	33.06	75	1.00	33.08	26.53
90	.75	33.11	100	.60	33.16	26.61
134	.16	33.48	150	.30	33.57	26.96
179	.62	33.70	(200)	.90	33.78	27.09

Station 2190; June 2; latitude 43°21′ N., longitude 49°17′ W.; depth 640 meters; dynamic height 971.017 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	4.08	32.74	0	4.08	32.74	26.01
25	.11	32.84	25	.11	32.84	26.39
50	−.28	33.07	50	−.28	33.07	26.58
76	−.45	33.24	75	−.45	33.24	26.73
101	−.08	33.45	100	−.10	33.44	26.87
151	.66	33.76	150	.65	33.76	27.09
202	1.62	34.12	200	1.55	34.10	27.30
303	3.00	34.64	300	3.00	34.63	27.61
394	3.46	34.79	400	3.50	34.79	27.69
598	3.72	34.89	600	3.70	34.89	27.75

Station 2191; June 2; latitude 43°19′ N., longitude 49°10′ W.; depth 1,783 meters; dynamic height 970.977 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	3.26	32.58	0	3.26	32.58	25.96
25	.11	32.80	25	.11	32.80	26.36
49	−1.09	32.99	50	−1.10	33.00	26.56
74	−.83	33.28	75	−.80	33.30	26.78
98	.29	33.65	100	.45	33.69	27.04
147	1.86	34.21	150	1.90	34.24	27.39
196	2.68	34.51	200	2.70	34.53	27.55
294	3.17	34.71	300	3.20	34.72	27.67
320	3.26	34.74	400	3.50	34.81	27.71
500	3.70	34.87	600	3.75	34.89	27.74
651	3.76	34.90	800	3.80	34.92	27.77
832	3.79	34.92	1,000	3.70	34.92	27.78
1,217	3.55	34.925				

Station 2192; June 3; latitude 43°15′ N., longitude 48°50′ W.; depth 2,112 meters; dynamic height 970.892 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	5.71	32.97	0	5.71	32.97	26.01
25	4.01	33.84	25	4.01	33.84	26.88
51	3.65	34.18	50	3.65	34.17	27.19
76	3.26	34.41	75	3.25	34.41	27.41
102	3.28	34.42	100	3.25	34.42	27.42
153	5.01	34.84	150	5.00	34.83	27.56
203	4.99	34.90	200	5.00	34.89	27.61
305	4.76	34.98	300	4.80	34.98	27.70
404	4.15	34.93	400	4.15	34.93	27.73
622	4.05	34.98	600	4.05	34.98	27.78
802	3.70	34.96	800	3.70	34.95	27.80
1,003	3.55	34.94	1,000	3.55	34.94	27.80
1,408	3.32	34.92				

Station 2193; June 3; latitude 43°12′ N., longitude 48°12′ W.; depth 3,200 meters; dynamic height 970.957 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	10.11	33.30	0	10.11	33.30	25.62
26	8.98	33.43	25	9.00	33.43	25.91
52	4.16	33.92	50	4.55	33.86	26.84
77	4.41	34.30	75	4.40	34.29	27.20
103	5.16	34.59	100	5.10	34.56	27.34
155	5.36	34.74	150	5.35	34.73	27.44
207	4.69	34.78	200	4.75	34.77	27.55
310	4.77	34.93	300	4.75	34.92	27.66
417	4.64	34.98	400	4.70	34.98	27.71
640	4.17	34.99	600	4.25	34.99	27.77
825	3.83	34.96	800	3.90	34.96	27.79
1,029	3.60	34.95	1,000	3.60	34.95	27.81
1,433	3.38	34.94				

Station 2194; June 3; latitude 43°13′ N., longitude 47°32′ W.; depth 3,594 meters; dynamic height 970.978 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	11.10	33.31	0	11.10	33.31	25.47
25	6.56	33.46	25	6.56	33.46	26.29
51	5.41	34.19	50	5.40	34.18	27.00
76	6.87	34.61	75	6.85	34.61	27.15
101	7.15	34.76	100	7.15	34.76	27.23
152	6.18	34.73	150	6.20	34.73	27.33
203	5.90	34.84	200	5.95	34.84	27.45
304	4.99	34.86	300	5.00	34.86	27.59
398	4.88	34.98	400	4.90	34.98	27.69
616	4.20	34.97	600	4.25	34.97	27.76
797	3.93	34.96	800	3.90	34.96	27.79
997	3.68	34.95	1,000	3.65	34.95	27.80
1,398	3.34	34.92				

Station 2195; June 3; latitude 42°42′ N., longitude 46°57′ W.; depth 3,996 meters; dynamic height 971.199 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	17.22	35.25	0	17.22	35.25	25.67
26	16.56	35.10	25	16.60	35.10	25.71
51	12.00	35.04	50	12.20	35.04	26.60
77	11.24	35.09	75	11.25	35.09	26.82
102	11.41	35.19	100	11.40	35.18	26.86
153	11.32	35.25	150	11.35	35.25	26.92
205	9.90	35.03	200	10.10	35.05	26.99
307	7.98	34.86	300	8.00	34.86	27.19
391	7.27	34.94	400	7.20	34.95	27.37
613	5.47	35.02	600	5.55	35.02	27.65
799	4.72	35.03	800	4.70	35.03	27.75
998	4.29	35.03	1,000	4.30	35.03	27.79
1,395	3.65	34.98				

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1936—Continued

Station 2196; June 3; latitude 43°07′ N., longitude 46°47′ W.; depth 4,070 meters; dynamic height 971.149 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	15.00	34.45	0	15.00	34.45	25.56
25	13.48	34.44	25	13.48	34.44	25.88
50	11.21	34.98	50	11.21	34.98	26.74
76	11.36	35.16	75	11.35	35.15	26.84
101	11.70	35.30	100	11.70	35.30	26.90
151	10.98	35.18	150	10.95	35.18	26.94
202	10.37	35.16	200	10.40	35.16	27.03
303	8.04	35.00	300	8.05	35.00	27.29
402	7.35	35.10	400	7.40	35.10	27.46
626	4.86	35.00	600	5.05	35.01	27.70
806	4.20	34.97	800	4.20	34.97	27.77
1,007	3.95	34.98	1,000	3.95	34.98	27.79
1,407	3.49	34.96				

Station 2197; June 4; latitude 43°36′ N., longitude 46°27′ W.; depth 4,536 meters; dynamic height 971.006 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	11.93	33.59	0	11.93	33.59	25.54
26	10.95	33.74	25	10.95	33.74	25.83
51	7.49	34.06	50	7.60	34.04	26.60
77	6.71	34.40	75	6.70	34.38	26.99
103	7.08	34.69	100	7.05	34.66	27.17
154	6.60	34.76	150	6.65	34.76	27.30
205	4.74	34.63	200	4.80	34.63	27.42
308	4.96	34.88	300	4.95	34.98	27.60
412	5.01	34.98	400	5.00	34.98	27.68
634	4.20	34.98	600	4.30	34.98	27.75
815	3.89	34.97	800	3.90	34.97	27.80
1,016	3.61	34.96	1,000	3.65	34.96	27.81
1,415	3.40	34.95				

Station 2198; June 4; latitude 43°41′ N., longitude 47°05′ W.; depth 4,152 meters; dynamic height 970.958 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	11.63	33.70	0	11.63	33.70	25.67
26	9.70	33.75	25	9.70	33.75	26.05
51	6.88	34.30	50	7.00	34.28	26.87
77	5.44	34.38	75	5.45	34.38	27.15
103	5.87	34.63	100	5.85	34.62	27.29
154	5.48	34.71	150	5.50	34.70	27.40
205	5.32	34.85	200	5.35	34.84	27.53
308	4.58	34.89	300	4.60	34.89	27.65
408	4.74	35.00	400	4.75	35.00	27.72
629	4.22	34.99	600	4.30	34.99	27.76
813	3.82	34.97	800	3.85	34.97	27.80
1,015	3.60	34.96	1,000	3.60	34.96	27.82
1,420	3.33	34.95				

Station 2199; June 4; latitude 43°50′ N., longitude 47°46′ W.; depth 3,896 meters; dynamic height 970.939 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	12.18	33.76	0	12.18	33.76	25.62
24	9.61	33.87	25	9.55	33.87	26.17
49	6.92	34.28	50	6.90	34.28	26.88
73	4.36	34.29	75	4.35	34.29	27.20
97	4.89	34.51	100	4.95	34.54	27.34
146	5.33	34.76	150	5.30	34.77	27.48
194	5.07	34.84	200	5.05	34.84	27.56
291	4.94	34.96	300	4.90	34.96	27.68
375	4.67	34.98	400	4.60	34.98	27.72
582	4.36	35.01	600	4.30	35.01	27.78
758	4.00	34.99	800	3.90	34.99	27.81
952	3.77	34.98	1,000	3.75	34.98	27.81
1,346	3.43	34.96				

Station 2200; June 4; latitude 43°58′ N., longitude 48°28′ W.; depth 3,310 meters; dynamic height 970.933 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	11.00	33.67	0	11.00	33.67	25.77
26	6.62	33.72	25	6.65	33.72	26.48
51	5.24	34.27	50	5.25	34.25	27.07
77	5.00	34.39	75	5.00	34.38	27.20
103	5.41	34.52	100	5.30	34.50	27.26
154	6.08	34.82	150	6.05	34.81	27.42
205	5.27	34.82	200	5.30	34.82	27.51
308	5.51	35.03	300	5.50	35.03	27.65
405	4.73	35.00	400	4.75	35.00	27.72
628	4.21	35.00	600	4.25	35.00	27.78
808	3.72	34.98	800	3.75	34.98	27.81
1,009	3.51	34.96	1,000	3.50	34.96	27.83
1,410	3.28	34.94				

Station 2201; June 4; latitude 44°03′ N., longitude 48°52′ W.; depth 1,344 meters; dynamic height 970.917 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	5.45	32.62	0	5.45	32.62	25.76
25	2.55	33.14	25	2.55	33.14	26.46
50	1.89	33.59	50	1.89	33.59	26.88
76	1.88	33.90	75	1.85	33.90	27.12
101	2.62	34.21	100	2.60	34.20	27.30
151	2.98	34.47	150	2.95	34.46	27.48
202	3.33	34.64	200	3.30	34.63	27.58
303	3.55	34.82	300	3.55	34.81	27.70
367	3.65	34.90	400	3.70	34.91	27.77
568	3.84	34.94	600	3.85	34.95	27.78
727	3.77	34.96	800	3.70	34.96	27.81
904	3.63	34.94	(1,000)	3.55	34.95	27.81

Station 2202; June 4; latitude 44°05′ N., longitude 48°59′ W.; depth 613 meters; dynamic height 970.975 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	4.40	32.67	0	4.40	32.67	25.92
25	.93	32.76	25	.93	32.76	26.27
51	−.42	33.15	50	−.40	33.13	26.64
76	−.25	33.34	75	−.25	33.34	26.80
102	.05	33.49	100	.00	33.47	26.90
153	1.63	34.16	150	1.55	34.10	27.30
203	2.65	34.53	200	2.55	34.51	27.56
305	3.09	34.69	300	3.05	34.68	27.64
311	3.09	34.69	(400)	3.35	34.78	27.69
484	3.55	-------	(600)	3.70	34.92	27.78

Station 2203; June 4; latitude 44°07′ N., longitude 49°04′ W.; depth 238 meters; dynamic height 971.001 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	5.78	32.65	0	5.78	32.65	25.74
26	1.78	32.72	25	1.80	32.72	26.18
51	−.49	33.13	50	−.50	33.11	26.62
77	−.32	33.26	75	−.35	33.25	26.72
103	−.32	33.30	100	−.30	33.29	26.75
154	1.16	33.96	150	1.05	33.90	27.18
206	2.55	34.50	200	2.45	34.46	27.52

Station 2204; June 4; latitude 44°08′ N., longitude 49°10′ W.; depth 86 meters; dynamic height 971.023 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	5.22	32.70	0	5.22	32.70	25.85
18	2.99	32.75	25	2.85	32.76	26.13
44	2.50	32.76	50	1.55	32.77	26.24
69	−.16	32.88	(75)	−.35	32.92	26.46

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1936—Continued

Station 2205; June 5; latitude 44°13′ N., longitude 49°41′ W.; depth 48 meters; dynamic height 971.030 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	9.84	33.14	0	9.84	33.14	25.54
27	5.52	33.12	25	5.60	33.12	26.14
41	5.03	33.14	(50)	4.90	33.16	26.25

Station 2206; June 5; latitude 44°57′ N., longitude 49°34′ W.; depth 66 meters; dynamic height 971.044 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	9.61	33.04	0	9.61	33.04	25.51
26	4.87	33.07	25	4.90	33.07	26.18
53	1.06	33.06	50	1.25	33.06	26.49

Station 2207; June 5; latitude 44°48′ N., longitude 49°08′ W.; depth 98 meters; dynamic height 971.046 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	7.00	32.61	0	7.00	32.61	25.57
26	2.33	32.64	25	2.50	32.64	26.07
51	−.72	32.81	50	−.70	32.80	26.39
77	−.89	33.07	75	−.90	33.06	26.60

Station 2208; June 5; latitude 44°47′ N., longitude 49°05′ W.; depth 221 meters; dynamic height 971.026 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	6.47	32.60	0	6.47	32.60	25.63
10	2.98	32.54	25	−.40	32.71	26.30
36	−1.23	32.86	50	−1.05	33.00	26.56
61	−.85	33.09	75	−.65	33.15	26.66
87	−.49	33.21	100	−.20	33.33	26.79
138	.61	33.69	150	.90	33.81	27.12
189	1.65	34.15	(200)	1.85	34.24	27.39

Station 2209; June 5; latitude 44°45′ N., longitude 48°58′ W.; depth 622 meters; dynamic height 970.984 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	5.99	32.52	0	5.99	32.52	25.62
26	−.40	32.82	25	−.35	32.81	26.38
51	−1.22	33.10	50	−1.20	33.09	26.63
77	−.35	33.37	75	−.45	33.37	26.83
103	.45	33.76	100	.30	33.71	27.07
154	1.67	34.17	150	1.55	34.14	27.33
205	1.95	34.27	200	1.90	34.26	27.41
308	3.03	34.65	300	3.00	34.63	27.61
404	3.46	34.81	400	3.45	34.80	27.70
605	3.75	34.92	600	3.75	34.92	27.77

Station 2210; June 5; latitude 44°44′ N., longitude 48°53′ W.; depth 1,481 meters; dynamic height 970.968 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	7.18	32.55	0	7.18	32.55	25.48
25	2.70	32.76	25	2.70	32.76	26.13
51	1.77	33.32	50	1.80	33.29	26.63
76	.21	33.54	75	.20	33.54	26.94
102	.99	33.92	100	.90	33.87	27.17
153	1.90	34.27	150	1.85	34.25	27.40
204	2.28	34.44	200	2.25	34.42	27.51
306	3.26	34.76	300	3.20	34.75	27.69
322	3.31	34.78	400	3.55	34.84	27.72
501	3.70	34.89	600	3.80	34.92	27.77
656	3.80	34.93	800	3.80	34.94	27.78
835	3.78	34.94	1,000	3.65	34.94	27.79
1,211	3.45	34.94				

Station 2211; June 5; latitude 44°36′ N., longitude 48°24′ W.; depth 2,634 meters; dynamic height 970.937 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	12.69	33.67	0	12.69	33.67	25.34
26	8.68	33.76	25	8.70	33.76	26.22
52	6.68	34.44	50	6.75	34.38	26.98
78	6.03	34.49	75	6.05	34.48	27.15
104	6.86	34.78	100	6.85	34.77	27.28
156	5.25	34.76	150	5.35	34.76	27.47
208	4.38	34.76	200	4.40	34.76	27.57
312	5.03	34.98	300	5.00	34.96	27.67
409	4.67	35.01	400	4.70	35.01	27.74
629	4.09	35.00	600	4.15	35.00	27.79
813	3.77	34.975	800	3.80	34.98	27.81
1,014	3.58	34.96	1,000	3.60	34.96	27.82
1,415	3.33	34.95				

Station 2212; June 5; latitude 44°33′ N., longitude 47°45′ W.; depth 3,640 meters; dynamic height 970.932 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	14.27	33.75	0	14.27	33.75	25.18
26	9.13	34.02	25	9.20	34.01	26.33
52	6.61	34.23	50	6.85	34.22	26.85
77	5.05	34.31	75	5.05	34.31	27.15
103	4.86	34.56	100	4.85	34.53	27.34
155	5.28	34.78	150	5.25	34.77	27.49
207	4.59	34.79	200	4.60	34.79	27.57
310	4.48	34.93	300	4.50	34.92	27.69
394	4.39	34.97	400	4.40	34.97	27.74
608	4.28	35.02	600	4.30	35.02	27.79
789	3.92	35.00	800	3.90	35.00	27.82
987	3.67	34.98	1,000	3.65	34.98	27.82
1,386	3.38	34.96				

Station 2213; June 6; latitude 44°32′ N., longitude 47°13′ W.; depth 3,795 meters; dynamic height 971.060 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	12.92	33.47	0	12.92	33.47	25.24
25	7.09	33.89	25	7.09	33.89	26.55
50	11.94	35.29	50	11.94	35.29	26.84
76	10.21	35.04	75	10.20	35.04	26.97
101	10.57	35.17	100	10.55	35.17	27.01
151	8.57	34.88	150	8.60	34.88	27.10
201	9.12	35.15	200	9.15	35.15	27.23
302	6.56	34.92	300	6.65	34.93	27.43
284	7.19	34.98	400	5.15	34.91	27.61
434	4.89	34.91	600	4.45	34.97	27.74
557	4.46	34.96	800	4.30	34.98	27.75
723	4.41	34.98	1,000	3.90	34.97	27.80
1,088	3.72	34.97				

Station 2214; June 6; latitude 44°33′ N., longitude 46°44′ W.; depth 3,859 meters; dynamic height 971.010 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	12.68	33.50	0	12.68	33.50	25.32
25	7.26	33.96	25	7.26	33.96	26.58
51	10.05	35.00	50	10.00	35.00	26.97
76	9.45	34.95	75	9.45	34.95	27.02
101	8.10	34.76	100	8.10	34.76	27.09
152	8.31	34.96	150	8.30	34.96	27.22
203	6.25	34.74	200	6.35	34.74	27.32
304	4.91	34.80	300	4.95	34.79	27.53
374	5.08	34.91	400	5.05	34.93	27.63
575	4.57	35.00	600	4.45	35.00	27.76
745	3.95	34.97	800	3.85	34.96	27.79
937	3.71	34.96	1,000	3.70	34.96	27.81
1,327	3.44	34.95				

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1936—Continued

Station 2215; June 6; latitude 44°49′ N., longitude 46°06′ W.; depth 3,640 meters; dynamic height 970.946 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	13.19	33.65	0	13.19	33.65	25.32
26	6.38	33.82	25	6.40	33.82	26.59
52	6.45	34.30	50	6.45	34.24	26.91
77	6.13	34.39	75	6.15	34.38	27.06
103	6.15	34.63	100	6.15	34.61	27.25
155	5.66	34.76	150	5.70	34.75	27.41
207	5.34	34.85	200	5.40	34.84	27.52
310	4.64	34.92	300	4.70	34.91	27.66
410	4.64	35.00	400	4.65	34.99	27.73
629	4.32	35.03	600	4.40	35.03	27.78
817	3.94	35.00	800	4.00	35.00	27.81
1,019	3.64	34.96	1,000	3.65	34.96	27.81
1,422	3.36	34.95				

Station 2216; June 6; latitude 45°19′ N., longitude 45°57′ W.; depth 3,585 meters; dynamic height 970.949 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	13.84	33.48	0	13.84	33.48	25.06
26	6.55	34.03	25	6.60	34.02	26.72
52	6.06	34.32	50	6.10	34.30	27.01
77	5.75	34.39	75	5.75	34.38	27.11
103	6.76	34.66	100	6.65	34.63	27.19
155	5.73	34.76	150	5.80	34.75	27.40
207	5.43	34.82	200	5.50	34.81	27.49
310	4.48	34.87	300	4.50	34.86	27.64
411	4.57	34.98	400	4.55	34.98	27.73
632	4.04	34.97	600	4.10	34.97	27.78
816	3.93	34.99	800	3.95	34.99	27.80
1,019	3.57	34.96	1,000	3.60	34.96	27.82
1,423	3.24	34.925				

Station 2217; June 6; latitude 45°20′ N., longitude 46°36′ W.; depth 3,429 meters; dynamic height 971.168 meters.

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	17.28	35.33	0	17.28	35.33	25.72
26	15.02	35.42	25	15.10	35.42	26.28
51	14.53	35.62	50	14.55	35.62	26.57
77	13.68	35.64	75	13.70	35.64	26.76
102	13.36	35.64	100	13.40	35.64	26.82
153	11.80	35.36	150	11.90	35.37	26.92
205	11.39	35.38	200	11.45	35.38	27.00
307	8.77	35.10	300	8.90	35.11	27.24
406	8.00	35.15	400	8.10	35.15	27.40
625	4.96	34.99	600	5.15	35.00	27.68
806	4.40	35.01	800	4.40	35.01	27.77
1,007	4.09	35.00	1,000	4.10	35.00	27.80
1,408	3.51	34.96				

Station 2218; June 7; latitude 45°18′ N., longitude 47°21′ W.; depth 2,944 meters; dynamic height 971.135 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	15.35	34.42	0	15.35	34.42	25.46
26	12.36	34.60	25	12.35	34.59	26.22
51	13.51	35.57	50	13.50	35.57	26.75
77	12.01	35.27	75	12.05	35.27	26.80
102	12.30	35.41	100	12.25	35.41	26.88
153	11.37	35.28	150	11.40	35.28	26.94
205	11.27	35.40	200	11.30	35.39	27.04
307	8.03	35.03	300	8.35	35.05	27.28
408	5.69	34.84	400	5.75	34.84	27.48
627	4.76	35.00	600	4.85	34.99	27.70
805	4.20	34.99	800	4.20	34.99	27.78
1,006	3.82	34.97	1,000	3.85	34.97	27.80
1,409	3.40	34.94				

Station 2219; June 7; latitude 45°31′ N., longitude 47°41′ W.; depth 1,646 meters; dynamic height 970.919 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	10.07	33.13	0	10.07	33.13	25.50
26	4.62	33.28	25	4.70	33.28	26.36
51	2.48	33.88	50	2.50	33.82	27.01
77	2.90	34.18	75	2.85	34.17	27.26
102	2.45	34.28	100	2.45	34.26	27.36
153	3.99	34.63	150	3.85	34.61	27.51
205	4.26	34.77	200	4.25	34.76	27.59
307	4.19	34.83	300	4.20	34.83	27.65
388	4.09	34.90	400	4.10	34.91	27.73
596	3.75	34.94	600	3.75	34.94	27.78
769	3.44	34.94	800	3.40	34.94	27.82
964	3.33	34.94	1,000	3.35	34.94	27.82
1,359	3.22	34.94				

Station 2220; June 7; latitude 45°40′ N., longitude 47°56′ W.; depth 1,143 meters; dynamic height 970.893 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	8.32	32.68	0	8.32	32.68	25.43
25	.37	33.22	25	.37	33.22	26.67
50	1.51	33.78	50	1.51	33.78	27.05
76	1.93	34.15	75	1.95	34.14	27.31
101	3.01	34.40	100	3.00	34.39	27.42
151	2.98	34.59	150	3.00	34.59	27.58
201	3.28	34.77	200	3.25	34.76	27.69
302	3.65	34.86	300	3.65	34.86	27.73
218	3.34	-------	400	3.75	34.90	27.75
398	3.72	34.90	600	3.70	34.93	27.78
595	3.72	34.93	800	3.60	34.94	27.80
790	3.59	34.95	1,000	3.55	34.94	27.80
988	3.52	34.94				

Station 2221; June 7; latitude 45°44′ N., longitude 48°03′ W.; depth 599 meters: dynamic height 970.939 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	9.24	32.46	0	9.24	32.46	25.11
25	1.81	32.86	25	1.81	32.86	26.29
51	−0.22	33.35	50	−0.20	33.34	26.79
76	0.52	33.86	75	0.50	33.86	27.18
102	1.79	34.26	100	1.70	34.22	27.39
153	2.34	34.44	150	2.30	34.42	27.51
204	2.85	34.63	200	2.80	34.62	27.62
306	3.32	34.76	300	3.30	34.75	27.68
356	3.62	34.86	400	3.70	34.88	27.74
550	3.74	34.90	(600)	3.75	34.90	27.75

Station 2222; June 7; latitude 45°49′ N , longitude 48°09′ W.; depth 169 meters; dynamic height 970.981 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	7.27	32.47	0	7.27	32.47	25.42
26	0.52	32.76	25	.65	32.76	26.29
51	−1.07	33.03	50	−1.05	33.02	26.57
77	−.28	33.51	75	−.30	33.50	26.93
103	.16	33.62	100	.10	33.61	27.00
154	1.35	34.07	150	1.20	34.03	27.27

Station 2223; June 7; latitude 45°53′ N., longitude 48°15′ W,; depth 115 meters; dynamic height 971.001 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	8.89	32.53	0	8.89	32.53	25.22
26	−.36	32.74	25	−.20	32.74	26.32
51	−1.47	32.92	50	−1.45	32.91	26.49
77	−1.17	33.15	75	−1.20	33.14	26.67
103	−.34	33.34	100	−.45	33.31	26.78

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1936—Continued

Station 2224: June 7; latitude 46°06′ N., longitude 48°35′ W.; depth 89 meters; dynamic height 970.999 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	9.75	33.09	0	9.75	33.09	25.52
25	4.68	33.07	25	4.68	33.07	26.20
51	1.52	33.18	50	1.60	33.17	26.56
76	.71	33.30	75	.75	33.30	26.71

Station 2225: June 7; latitude 46°21′ N., longitude 48°57′ W.; depth 68 meters; dynamic height 971.004 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	9.27	33.16	0	9.27	33.16	25.66
26	5.15	33.14	25	5.30	33.14	26.19
52	2.30	33.25	50	2.40	33.24	26.56

Station 2226: June 7; latitude 46°20′ N., longitude 48°34′ W.; depth 91 meters; dynamic height 971.008 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	8.81	33.14	0	8.81	33.14	25.71
26	4.82	33.11	25	4.95	33.11	26.20
51	1.36	33.24	50	1.50	33.24	26.62
77	.83	33.30	75	.85	33.30	26.71

Station 2227: June 7; latitude 46°18′ N., longitude 48°08′ W.; depth 114 meters; dynamic height 971.019 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	9.78	32.94	0	9.78	32.94	25.40
23	4.82	33.00	25	4.80	32.99	26.13
49	.18	32.86	50	.10	32.86	26.40
74	−.25	33.20	75	−.25	33.20	26.69
100	.06	33.38	100	.06	33.38	26.82

Station 2228: June 7; latitude 46°16′ N., longitude 47°44′ W.; depth 167 meters; dynamic height 971.017 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	5.57	32.44	0	5.57	32.44	25.61
23	2.11	32.54	25	1.95	32.56	26.04
49	−1.15	32.86	50	−1.15	32.86	26.44
74	−1.17	33.06	75	−1.15	33.07	26.62
100	−.24	33.44	100	−.24	33.44	26.88
152	−.08	33.52	150	−.10	33.52	26.94

Station 2229: June 8; latitude 46°15′ N., longitude 47°16′ W.; depth 622 meters; dynamic height 970.920 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	8.59	32.60	0	8.59	32.60	25.33
26	1.52	33.00	25	1.05	32.99	26.41
51	−.07	33.58	50	−.05	33.57	26.98
77	.91	33.96	75	.85	33.95	27.23
102	1.38	34.20	100	1.30	34.17	27.38
153	2.58	34.50	150	2.50	34.48	27.53
205	3.07	34.70	200	3.05	34.68	27.64
307	3.51	34.82	300	3.50	34.81	27.71
381	3.62	34.86	400	3.65	34.87	27.74
576	3.75	34.92	(600)	3.75	34.92	27.77

Station 2230: June 8; latitude 46°14′ N., longitude 47°01′ W.; depth 1,234 meters; dynamic height 970.897 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	6.51	32.78	0	6.51	32.78	25.76
26	1.57	33.06	25	1.60	33.05	26.46
51	1.00	33.66	50	1.00	33.64	26.97
77	1.32	34.13	75	1.30	34.12	27.34
103	2.04	34.38	100	1.95	34.36	27.49
154	3.04	34.68	150	3.00	34.67	27.65
205	3.24	34.74	200	3.25	34.73	27.66
308	3.61	34.83	300	3.60	34.83	27.71
223	3.29	-------	400	3.75	34.89	27.74
408	3.72	34.89	600	3.75	34.92	27.77
610	3.73	34.92	800	3.60	34.94	27.80
809	3.61	34.94	1,000	3.60	34.94	27.80
1,014	3.58	34.93				

Station 2231: June 8; latitude 46°12′ N., longitude 46°32′ W.; depth 613 meters; dynamic height 970.838 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	7.80	33.22	0	7.80	33.22	25.93
26	3.09	34.17	25	3.10	34.15	27.22
51	3.66	34.49	50	3.60	34.48	27.43
77	4.42	34.69	75	4.40	34.68	27.50
103	4.63	34.80	100	4.65	34.79	27.57
154	4.46	34.86	150	4.45	34.85	27.64
206	4.50	34.96	200	4.50	34.96	27.72
309	4.19	34.97	300	4.20	34.97	27.77
405	3.93	34.97	400	3.95	34.97	27.79
597	3.70	34.95	600	3.70	34.95	27.80

Station 2232; June 8; latitude 46°10′ N., longitude 45°53′ W.; depth 914 meters; dynamic height 970.922 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	13.66	33.62	0	13.66	33.62	25.22
26	6.48	33.80	25	6.55	33.80	26.56
51	4.78	34.18	50	4.80	34.16	27.05
77	4.88	34.42	75	4.85	34.42	27.26
103	4.98	34.53	100	4.95	34.51	27.32
154	5.60	34.86	150	5.55	34.86	27.52
205	4.84	34.86	200	4.85	34.86	27.60
308	4.68	34.96	300	4.70	34.96	27.70
67	4.89	-------	400	4.60	35.01	27.75
399	4.58	35.01	600	3.80	34.96	27.80
599	3.82	34.96	800	3.40	34.94	27.82
848	3.36	34.94				

Station 2233; June 8; latitude 46°06′ N., longitude 45°17′ W.; depth 2,451 meters; dynamic height 970.995 meters.

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	14.73	32.96	0	14.73	32.96	24.48
26	4.67	33.58	25	4.70	33.57	26.60
51	6.09	34.30	50	6.05	34.27	26.99
77	6.36	34.43	75	6.35	34.42	27.07
103	7.80	34.82	100	7.70	34.81	27.19
154	6.77	34.74	150	6.75	34.74	27.27
205	7.54	35.03	200	7.50	35.02	27.38
308	5.96	34.97	300	6.05	34.97	27.55
411	4.71	34.95	400	4.85	34.95	27.67
632	3.88	34.94	600	3.90	34.94	27.77
816	3.71	34.95	800	3.75	34.95	27.79
1,019	3.53	34.96	1,000	3.55	34.96	27.82
1,423	3.39	34.95				

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1936—Continued

Station 2234; June 8; latitude 46°05′ N., longitude 44°47′ W.; depth 3,502 meters; dynamic height 970.952 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	14.94	33.18	0	14.94	33.18	24.60
26	3.77	33.45	25	3.80	33.44	26.59
51	7.42	34.54	50	7.40	34.56	27.04
77	6.56	34.53	75	6.60	34.55	27.14
103	5.63	34.50	100	5.65	34.54	27.25
154	5.83	34.75	150	5.80	34.74	27.39
206	5.31	34.79	200	5.40	34.79	27.48
309	4.53	34.89	300	4.55	34.88	27.65
410	4.64	35.00	400	4.65	34.99	27.73
630	3.68	34.94	600	3.80	34.94	27.78
814	3.55	34.94	800	3.55	34.94	27.80
1,017	3.37	34.94	1,000	3.40	34.94	27.82
1,421	3.32	34.94				

Station 2235; June 20; latitude 53°44′ N., longitude 55°51′ W.; depth 100 meters; dynamic height 1,454.835 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	4.26	27.74	0	4.26	27.74	22.02
26	−.97	32.49	25	−.80	32.48	26.13
53	−1.55	32.68	50	−1.50	32.67	26.30
79	−1.61	32.78	75	−1.60	32.77	26.39
			(100)	−1.60	32.85	26.45

Station 2236; June 20; latitude 53°51′ N., longitude 55°38′ W.; depth 182 meters; dynamic height 1,454.780 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	2.42	32.16	0	2.42	32.16	25.69
26	.62	32.48	25	.70	32.47	26.05
52	−1.52	32.82	50	−1.50	32.80	26.41
78	−1.48	32.91	75	−1.50	32.90	26.48
103	−1.55	33.03	100	−1.55	33.01	26.58
155	−1.13	33.44	150	−1.15	33.41	26.90
176	−1.04	33.50				

Station 2237; June 20; latitude 53°59′ N., longitude 55°23′ W.; depth 144 meters; dynamic height 1,454.735 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	2.00	32.44	0	2.00	32.44	25.95
26	1.03	32.54	25	1.10	32.54	26.09
52	−1.51	33.11	50	−1.50	33.05	26.58
77	−1.39	33.26	75	−1.40	33.25	26.76
103	−1.21	33.46	100	−1.25	33.43	26.91
137	−.54	33.76	(150)	−.15	33.89	27.24

Station 2238; June 20; latitude 54°12′ N., longitude 55°00′ W.; depth 166 meters; dynamic height 1,454.731 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	1.73	32.44	0	1.73	32.44	25.97
16	1.71	32.43	25	0.75	32.58	26.14
42	−1.47	32.89	50	−1.50	32.96	26.53
68	−1.47	33.13	75	−1.35	33.23	26.75
94	−1.08	33.52	100	−1.00	33.58	27.02
157	.22	33.97	150	.10	33.93	27.25

Station 2239; June 20; latitude 54°26′ N., longitude 54°32′ W.; depth 200 meters; dynamic height 1,454.729 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	1.52	32.53	0	1.52	32.53	26.05
25	.20	32.62	25	.20	32.62	26.20
50	−1.46	33.18	50	−1.46	33.18	26.71
75	−1.38	33.34	75	−1.38	33.34	26.84
101	−1.21	33.48	100	−1.25	33.47	26.95
151	−.27	33.82	150	−.30	33.82	27.19
186	.62	34.10	(200)	1.05	34.21	27.43

Station 2240; June 20; latitude 54°42′ N., longitude 54°02′ W.; depth 268 meters; dynamic height 1,454.695 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	−0.37	32.46	0	−0.37	32.46	26.09
16	−.72	33.00	25	−1.05	33.15	26.67
42	−1.43	33.35	50	−1.40	33.42	26.91
68	−1.24	33.56	75	−1.20	33.61	27.06
94	−1.06	33.68	100	−1.00	33.70	27.12
147	−.24	33.92	150	−.20	33.94	27.28
200	.89	34.20	200	.90	34.20	27.43
252	2.16	34.51				

Station 2241; June 20; latitude 54°52′ N., longitude 53°42′ W.; depth 623 meters; dynamic height 1,454.602 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	2.02	33.25	0	2.02	33.25	26.60
24	−.14	33.82	25	−.15	33.83	27.19
48	.43	34.04	50	.45	34.05	27.33
71	.62	34.12	75	.70	34.14	27.39
95	1.52	34.36	100	1.60	34.38	27.52
143	2.22	34.52	150	2.30	34.53	27.59
191	2.70	34.63	200	2.80	34.65	27.64
286	3.52	34.85	300	3.50	34.83	27.72
295	3.43	34.81	400	3.60	34.89	27.76
490	3.61	34.92	(600)	3.65	34.92	27.78

Station 2242; June 20–21; latitude 54°55′ N., longitude 53°35′ W.; depth 1,368 meters; dynamic height 1,454.563 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	1.66	33.06	0	1.66	33.06	26.46
25	2.55	33.86	25	2.55	33.86	27.03
51	4.14	34.43	50	4.15	34.43	27.33
76	2.53	34.50	75	2.55	34.50	27.55
101	3.66	34.80	100	3.65	34.80	27.68
152	3.61	34.89	150	3.60	34.89	27.76
203	3.60	34.90	200	3.60	34.90	27.77
304	3.60	34.94	300	3.60	34.94	27.80
385	3.60	34.95	400	3.60	34.94	27.80
503	3.58	34.93	600	3.55	34.94	27.80
776	3.51	34.94	800	3.50	34.94	27.81
974	3.49	34.94	1,000	3.50	34.94	27.81
1,274	3.38	34.94				

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1936—Continued

Station 2243; June 21; latitude 55°08′ N., longitude 53°12′ W.; depth 2,708 meters; dynamic height 1,454.530 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	4.32	34.47	0	4.32	34.47	27.35
25	4.30	34.49	25	4.30	34.49	27.37
51	3.77	34.70	50	3.75	34.69	27.58
76	3.69	34.77	75	3.65	34.77	27.66
101	3.62	34.86	100	3.60	34.85	27.73
152	3.61	34.92	150	3.60	34.92	27.79
203	3.60	34.92	200	3.60	34.92	27.79
304	3.59	34.94	300	3.60	34.93	27.79
408	3.61	34.93	400	3.60	34.93	27.79
611	3.58	34.95	600	3.60	34.95	27.81
814	3.55	34.95	800	3.55	34.95	27.81
1,016	3.51	34.96	1,000	3.55	34.96	27.82
1,524	3.30	34.95	1,500	3.30	34.95	27.84
2,034	2.98	34.96	2,000	3.00	34.96	27.88
1,763	3.17	-------	2,500	2.70	34.97	27.91
2,568	2.62	34.97				

Station 2244; June 21; latitude 55°27′ N., longitude 52°34′ W.; depth 3,216 meters; dynamic height 1,454.538 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	4.90	34.62	0	4.90	34.62	27.41
24	4.85	34.63	25	4.85	34.63	27.42
48	4.54	34.72	50	4.40	34.73	27.54
72	3.66	34.79	75	3.65	34.79	27.67
96	3.55	34.80	100	3.50	34.80	27.70
144	3.39	34.83	150	3.40	34.84	27.74
192	3.51	34.89	200	3.50	34.89	27.77
288	3.51	34.91	300	3.50	34.91	27.79
320	3.54	34.92	400	3.50	34.91	27.79
481	3.48	34.91	600	3.45	34.92	27.80
654	3.43	34.92	800	3.40	34.93	27.81
827	3.39	34.93	1,000	3.35	34.93	27.81
1,282	3.26	34.93	1,500	3.25	34.94	27.83
1,767	3.23	34.94	2,000	3.15	34.94	27.84
2,286	3.09	-------	2,500	2.90	34.95	27.88
2,460	2.95	34.95	3,000	2.15	34.93	27.92
3,006	2.14	34.93				

Station 2245; June 21; latitude 56°05′ N., longitude 51°17′ W.; depth 3,616 meters; dynamic height 1,454.571 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	5.36	34.61	0	5.36	34.61	27.35
26	5.35	34.61	25	5.35	34.61	27.35
51	4.66	34.56	50	4.70	34.56	27.38
77	3.55	34.66	75	3.55	34.66	27.58
103	3.45	34.70	100	3.45	34.69	27.61
154	3.70	34.80	150	3.70	34.80	27.68
206	3.58	34.82	200	3.55	34.82	27.71
309	3.75	34.90	300	3.75	34.89	27.74
401	3.69	34.92	400	3.70	34.92	27.78
602	3.53	34.92	600	3.50	34.92	27.80
803	3.42	34.90	800	3.40	34.91	27.80
1,001	3.35	34.91	1,000	3.35	34.91	27.80
1,505	3.27	34.93	1,500	3.25	34.93	27.82
2,016	3.25	34.93	2,000	3.25	34.93	27.82
2,508	3.04	34.95	2,500	3.05	34.95	27.86
2,776	2.86	-------	3,000	2.65	34.93	27.88
3,009	2.65	34.93	3,500	1.90	34.92	27.94

Station 2,246; June 22; latitude 56°41′ N., longitude 50°08′ W.; depth 3,654 meters; dynamic height 1,454.553 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	5.05	34.70	0	5.05	34.70	27.45
25	5.04	34.70	25	5.04	34.70	27.45
50	4.87	34.72	50	4.87	34.72	27.49
76	4.13	34.75	75	4.15	34.75	27.59
101	3.50	34.78	100	3.50	34.78	27.68
151	3.40	34.82	150	3.40	34.82	27.73
201	3.42	34.86	200	3.40	34.86	27.76
302	3.45	34.90	300	3.45	34.90	27.78
385	3.48	34.90	400	3.50	34.90	27.78
579	3.46	34.91	600	3.45	34.91	27.79
774	3.39	34.91	800	3.40	34.91	27.80
970	3.32	34.91	1,000	3.35	34.91	27.80
1,465	3.25	34.92	1,500	3.25	34.92	27.82
1,967	3.24	34.92	2,000	3.25	34.92	27.82
2,544	3.08	34.94	2,500	3.10	34.94	27.85
2,815	2.93	-------	3,000	2.75	34.96	27.90
3,046	2.71	34.96	3,500	1.95	34.94	27.95
3,546	1.84	34.94				

Station 2,247; June 22; latitude 57°16′ N., longitude 49°02′ W.; depth 3,672 meters; dynamic height 1,454.547 meters.

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	5.28	34.71	0	5.28	34.71	27.43
26	5.06	34.80	25	5.05	34.80	27.53
51	4.65	34.82	50	4.65	34.82	27.60
77	4.04	34.92	75	4.05	34.92	27.74
103	3.93	34.91	100	3.95	34.91	27.74
155	3.87	34.90	150	3.90	34.90	27.74
206	3.88	34.92	200	3.90	34.92	27.76
309	3.79	34.92	300	3.80	34.92	27.77
403	3.78	34.92	400	3.80	34.92	27.77
602	3.71	34.93	600	3.70	34.93	27.78
801	3.50	34.93	800	3.50	34.93	27.80
997	3.37	34.93	1,000	3.40	34.93	27.81
1,503	3.26	34.92	1,500	3.25	34.92	27.82
2,013	3.24	34.93	2,000	3.25	34.93	27.82
2,512	3.08	34.95	2,500	3.10	34.95	27.86
2,736	2.93	-------	3,000	2.70	34.95	27.89
3,018	2.70	34.95	3,500	1.60	34.92	27.96
3,472	1.69	34.92				

Station 2,248; June 22–23; latitude 57°57′ N., longitude 47°50′ W.; depth 3,352 meters; dynamic height height 1,454.542 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	5.24	34.74	0	5.24	34.74	27.46
26	5.03	34.80	25	5.05	34.80	27.53
51	4.67	34.76	50	4.70	34.76	27.54
77	3.58	34.77	75	3.60	34.77	27.67
103	3.41	34.78	100	3.40	34.78	27.69
154	3.46	34.83	150	3.45	34.83	27.72
205	3.55	34.88	200	3.55	34.87	27.75
308	3.66	34.91	300	3.65	34.91	27.77
418	3.54	34.91	400	3.55	34.91	27.78
622	3.45	34.91	600	3.45	34.91	27.79
822	3.32	34.93	800	3.35	34.93	27.81
1,020	3.28	34.93	1,000	3.30	34.93	27.82
1,530	3.22	34.93	1,500	3.25	34.93	27.82
2,042	3.20	34.95	2,000	3.20	34.95	27.85
2,511	2.93	-------	2,500	2.95	34.96	27.88
2,568	2.89	34.96	3,000	2.40	34.95	27.92
3,075	2.25	34.95				
3,242	1.48	34.92				

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1936—Continued

Station 2,249; June 23; latitude 58°38′ N., longitude 46°36′ W.; depth 2,634 meters; dynamic height 1,454.552 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	5.70	34.78	0	5.70	34.78	27.43
23	5.66	34.80	25	5.65	34.80	27.46
46	5.37	34.83	50	5.25	34.84	27.54
70	4.75	34.89	75	4.75	34.91	27.65
93	4.72	34.97	100	4.70	34.97	27.71
140	4.48	34.96	150	4.45	34.96	27.73
186	4.45	34.97	200	4.40	34.97	27.74
279	4.08	34.94	300	4.05	34.95	27.76
301	4.06	34.95	400	3.95	34.94	27.76
456	3.91	34.94	600	3.80	34.93	27.77
614	3.77	34.93	800	3.55	34.93	27.79
776	3.57	34.93	1,000	3.40	34.94	27.82
1,204	3.29	34.94	1,500	3.20	34.95	27.85
1,542	3.21	34.95	2,000	2.90	34.94	27.88
1,894	3.02	34.96	(2,500)	1.65	34.92	27.96
2,236	2.40	34.93				

Station 2250; June 23; latitude 59°00′ N., longitude 45°25′ W.; depth 2,403 meters; dynamic height 1,454.548 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	5.66	34.78	0	5.66	34.78	27.44
26	5.51	34.82	25	5.50	34.82	27.50
51	5.34	34.83	50	5.35	34.83	27.52
77	4.68	34.95	75	4.70	34.95	27.69
102	4.58	34.96	100	4.55	34.96	27.72
153	4.58	34.98	150	4.60	34.98	27.72
205	4.68	34.98	200	4.65	34.98	27.72
307	4.58	35.00	300	4.60	35.00	27.74
406	4.25	34.97	400	4.25	34.97	27.76
604	4.03	34.97	600	4.05	34.97	27.78
800	3.70	34.96	800	3.70	34.96	27.81
992	3.49	34.96	1,000	3.50	34.96	27.83
1,347	3.32	34.95	1,500	3.20	34.95	27.85
1,698	2.97	34.95	2,000	2.60	34.92	27.88
2,019	2.54	34.92				

Station 2251; June 23; latitude 59°12′ N., longitude 45°02′ W.; depth 2,032 meters; dynamic height 1,454.564 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	5.75	34.60	0	5.75	34.60	27.29
26	5.45	34.70	25	5.45	34.70	27.40
51	5.30	34.80	50	5.30	34.79	27.49
77	4.97	34.96	75	4.95	34.96	27.67
103	5.00	34.99	100	5.00	34.99	27.69
154	5.04	35.02	150	5.05	35.02	27.71
206	4.98	35.03	200	5.00	35.03	27.72
309	4.75	35.02	300	4.80	35.02	27.74
410	4.64	35.00	400	4.65	35.00	27.74
613	4.21	34.98	600	4.20	34.98	27.77
814	3.86	35.00	800	3.90	35.00	27.82
1,014	3.61	34.97	1,000	3.65	34.97	27.82
1,360	3.33	34.95	1,500	3.20	34.95	27.85
1,677	2.98	34.95	(2,000)	2.40	34.92	27.90
1,978	2.47	34.925				

Station 2252; June 23; latitude 59°22′ N., longitude 44°44′ W.; depth 1,696 meters; dynamic height 1,454.607 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	4.79	34.18	0	4.79	34.18	27.07
25	5.35	34.62	25	5.35	34.62	27.36
50	5.44	34.72	50	5.44	34.72	27.42
75	5.58	34.98	75	5.57	34.98	27.61
100	5.61	35.02	100	5.61	35.02	27.64
150	5.46	35.05	150	5.46	35.05	27.68
200	5.52	35.06	200	5.52	35.06	27.68
300	5.10	35.02	300	5.11	35.02	27.70
378	4.94	35.02	400	4.90	35.02	27.73
566	4.53	35.00	600	4.50	35.00	27.75
754	4.22	34.99	800	4.20	34.99	27.78
898	4.02	34.98	1,000	3.90	34.98	27.80
1,179	3.65	34.97	(1,500)	3.15	34.94	27.84
1,465	3.20	34.94				

Station 2253; June 24; latitude 59°26′ N., longitude 44°37′ W.; depth 1,096 meters; dynamic height 1,454.703 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	1.27	33.26	0	1.27	33.26	26.65
26	1.89	33.52	25	1.90	33.52	26.83
52	2.82	33.82	50	2.75	33.80	26.97
78	4.12	34.30	75	4.05	34.24	27.20
104	5.03	34.66	100	5.00	34.61	27.39
156	4.13	34.76	150	4.15	34.75	27.59
207	4.75	34.93	200	4.70	34.91	27.66
311	4.96	35.00	300	4.95	35.00	27.70
366	4.97	35.00	400	4.95	35.00	27.70
550	4.89	35.00	600	4.85	35.00	27.71
743	4.85	35.00	800	4.80	35.00	27.72
940	4.57	35.00	(1,000)	4.40	35.00	27.76

Station 2254; June 24; latitude 59°32′ N., longitude 44°27′ W.; depth 643 meters; dynamic height 1,454.701 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	−0.10	32.34	0	−0.10	32.34	25.99
26	−.82	33.15	25	−.80	33.14	26.66
51	−.80	33.52	50	−.80	33.51	26.96
77	.44	33.82	75	.35	33.81	27.15
103	2.12	34.30	100	1.95	34.22	27.38
154	2.77	34.95	150	2.70	34.95	27.89
206	3.60	34.95	200	3.50	34.95	27.82
309	4.81	34.93	300	4.80	34.93	27.66
399	4.86	34.95	400	4.85	34.95	27.67
602	4.83	34.99	600	4.85	34.99	27.70

Station 2255; June 24; latitude 59°38′ N., longitude 44°17′ W.; depth 162 meters; dynamic height 1,454.755 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	−0.08	32.10	0	−0.08	32.10	25.79
26	−.46	32.78	25	−.45	32.76	26.34
52	−.49	33.36	50	−.50	33.32	26.79
79	−.34	33.64	75	−.40	33.62	27.04
105	.21	33.85	100	.10	33.81	27.16
157	2.15	34.31	150	1.90	34.26	27.41

Table of Oceanograghic Data—Continued

STATIONS OCCUPIED IN 1936—Continued

Station 2256; June 24; latitude 59°48′ N., longitude 44°10′ W.; depth 80 meters; dynamic height 1,454.786 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	0.00	31.95	0	0.00	31.95	25.67
25	−.18	32.18	25	−.18	32.18	25.86
50	−.59	32.99	50	−.59	32.99	26.53
65	−.43	33.21	(75)	−.25	33.33	26.79

Station 2257; June 25; latitude 60°09′ N., longitude 51°15′ W.; depth 3,286 meters; dynamic height 1,454.564 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	5.24	34.74	0	5.24	34.74	27.46
24	5.17	34.76	25	5.15	34.76	27.49
47	4.94	34.76	50	4.90	34.76	27.52
71	4.73	34.82	75	4.70	34.83	27.59
94	4.53	34.89	100	4.50	34.89	27.66
141	4.43	34.93	150	4.45	34.94	27.71
188	4.46	34.97	200	4.45	34.97	27.74
282	4.35	34.96	300	4.30	34.96	27.74
312	4.28	34.96	400	4.15	34.96	27.76
475	4.09	34.97	600	3.95	34.97	27.79
642	3.91	34.965	800	3.75	34.96	27.80
814	3.71	34.96	1,000	3.55	34.95	27.81
1,269	3.39	34.94	1,500	3.30	34.94	27.83
1,754	3.26	34.94	2,000	3.10	34.95	27.86
2,534	2.72	34.955	2,500	2.75	34.95	27.89
2,967	2.14	34.94	3,000	2.05	34.94	27.94
3,115	1.79	34.94				

Station 2258; June 25; latitude 60°30′ N., longitude 50°07′ W.; depth 3,032 meters; dynamic height 1,454.551 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	5.19	34.59	0	5.19	34.59	27.35
24	5.07	34.60	25	5.05	34.60	27.37
49	4.82	34.74	50	4.80	34.74	27.51
73	4.66	34.82	75	4.65	34.83	27.60
98	4.46	34.92	100	4.45	34.92	27.70
147	4.56	34.97	150	4.55	34.97	27.73
195	4.49	34.97	200	4.50	34.97	27.73
293	4.38	34.98	300	4.40	34.98	27.74
403	4.12	34.98	400	4.15	34.98	27.77
606	3.95	34.98	600	3.95	34.98	27.79
811	3.69	34.97	800	3.70	34.97	27.82
1,018	3.54	34.97	1,000	3.55	34.97	27.83
1,543	3.26	34.95	1,500	3.30	34.95	27.84
2,116	2.83	34.95	2,000	2.85	34.95	27.88
2,227	2.59	34.94	2,500	2.15	34.93	27.92
2,742	1.75	34.93	(3,000)	1.30	34.92	27.98

Station 2259; June 25–26; latitude 60°37′ N., longitude 49°38′ W.; depth 2,855 meters; dynamic height 1,454.557 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	5.08	34.48	0	5.08	34.48	27.27
25	5.00	34.58	25	5.00	34.58	27.36
51	4.87	34.73	50	4.90	34.73	27.49
76	4.58	34.81	75	4.55	34.81	27.60
102	4.32	34.88	100	4.35	34.87	27.67
153	4.54	34.96	150	4.55	34.96	27.72
203	4.55	34.98	200	4.55	34.98	27.73
305	4.33	34.97	300	4.35	34.97	27.75
370	4.22	34.96	400	4.20	34.96	27.76
558	3.93	34.96	600	3.90	34.96	27.79
748	3.81	34.95	800	3.75	34.95	27.79
940	3.57	34.96	1,000	3.50	34.96	27.83
1,426	3.24	34.95	1,500	3.20	34.95	27.85
1,928	2.92	34.95	2,000	2.90	34.95	27.87
2,082	2.82	34.96	2,500	2.50	34.94	27.90
2,473	2.55	34.94				
2,668	2.10	34.92				

Station 2260; June 26; latitude 60°44.5′ N., longitude 49°25′ W.; depth 2,524 meters; dynamic height 1,454.657 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	4.12	34.35	0	4.12	34.35	27.28
25	4.12	34.34	25	4.12	34.34	27.27
50	3.98	34.38	50	3.98	34.38	27.31
74	3.87	34.51	75	3.85	34.51	27.43
99	3.92	34.60	100	3.95	34.60	27.49
149	4.19	34.79	150	4.20	34.79	27.62
199	4.31	34.83	200	4.30	34.83	27.64
298	4.67	34.95	300	4.65	34.95	27.70
312	4.69	34.95	400	4.75	34.97	27.70
439	4.76	34.97	600	4.65	35.00	27.74
547	4.72	35.00	800	4.40	34.99	27.75
636	4.58	35.00	1,000	4.15	34.98	27.77
946	4.24	34.98	1,500	3.45	34.94	27.81
1,131	3.99	34.97	(2,000)	2.80	34.92	27.86
1,343	3.64	34.96				
1,588	3.34	34.93				

Station 2261; June 26; latitude 60°51′ N., longitude 49°11′ W.; depth 89 meters; dynamic height 1,454.711 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	2.74	33.78	0	2.74	33.78	26.95
25	2.60	33.80	25	2.60	33.80	26.98
50	2.59	33.82	50	2.59	33.82	27.00
75	1.66	34.02	75	1.66	34.02	27.24

Station 2262; June 26; latitude 60°57′ N., longitude 49°00′ W.; depth 177 meters; dynamic height 1,454.749 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	1.45	33.04	0	1.45	33.04	26.47
25	1.41	33.04	25	1.41	33.04	26.47
49	.88	33.27	50	.90	33.28	26.69
74	1.38	33.84	75	1.35	33.84	27.11
98	1.53	33.92	100	1.55	33.92	27.16
147	1.61	33.95	150	1.65	33.95	27.18

Station 2263; June 26; latitude 61°02.2′ N., longitude 48°50′ W.; depth 114 meters; dynamic height 1,454.762 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	1.62	32.94	0	1.62	32.94	26.37
24	.88	33.02	25	.85	33.02	26.49
48	.73	33.13	50	.75	33.15	26.60
72	1.03	33.50	75	1.05	33.52	26.88
96	1.15	33.68	100	1.15	33.70	27.01

Station 2264; June 26; latitude 61°06.5′ N., longitude 48°37.7′ W.; depth 229 meters; dynamic height 1,454.834 meters

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity ‰	Depth, meters	Temperature °C	Salinity ‰	σ_t
0	4.19	30.05	0	4.19	30.05	23.86
24	1.81	32.46	25	1.80	32.48	25.99
47	1.54	32.91	50	1.50	32.94	26.38
94	1.06	33.25	75	1.25	33.14	26.56
			100	1.00	33.28	26.69
			(150)	.75	33.52	26.90

Contribution No. 159

Reprinted from BIOLOGICAL BULLETIN, Vol. LXXIV, No. 1, 83–92, Feb., 1938
Printed in U. S. A.

THE DISTRIBUTION OF AMMONIA IN THE WATERS OF THE GULF OF MAINE

ALFRED C. REDFIELD AND ANCEL B. KEYS

(*From the Woods Hole Oceanographic Institution*[1] *and the Biological Laboratories, Harvard University*)

In the decomposition of organic residues in the sea ammonia is apparently the first simple inorganic compound of nitrogen to be set free. Since it does not commonly occur in large quantities, it is evidently oxidized rapidly to nitrate and nitrite. As an ephemeral intermediate in the cycle of regeneration of nitrate, it is of interest in indicating the places in which the decomposition of nitrogenous material is taking place.

The present paper presents the results of a survey of the occurrence of ammonia in the waters of the Gulf of Maine based on observations made during cruises of the "Atlantis" in September, 1933 and May and June, 1934. The only previous measurements of ammonia in these waters of which we are aware are those made by Seiwell (1931) in Penobscot and Frenchman's Bays and those recorded by Rakestraw (1936) in a study of the occurrence of nitrite in the sea. Our results are correlated with the studies of nitrite made by Rakestraw of the phosphorus cycle by Redfield, Smith and Ketchum (1937), and with observations on the distribution of plankton, based on collections made during these cruises.

METHODS

Ammonia was determined by the Teorell titration of the vacuum distillate as described by Krogh (1934). The apparatus could be used practically on shipboard, using alcohol lamps burning pure alcohol for heating and a Cenco Hyvac pump as a source of low pressure. Ammonia-free water was prepared ashore. It was found necessary to steam out the apparatus before the start of each series of analyses and to make blank analyses between each pair of unknowns. To be reliable, all determinations must be made in duplicate, since unforeseen contamination frequently occurred.

The sea water samples were taken in Nansen reversing bottles, from which they were immediately transferred, with double rinsing, to glass-stoppered bottles. These were stored in the refrigerator and analyzed as quickly as possible. Experiments recorded in Table I showed that sea water stored for about eight hours underwent no appreciable change in ammonia content. With longer periods of storage there is a progressive decrease in the ammonia content, which is not prevented by the addition of 0.1 per cent mercuric chloride (Keys, Christensen and Krogh, 1935). The reason for this loss is unknown.

---

[1] Contribution No. 159.

RESULTS

The positions of the stations at which reasonably complete and satisfactory observations on the distribution of ammonia were obtained in September, 1933 and May, 1934 are shown in Figs. 1 and 2. Observations were also made at six stations in the Gulf between June 25 and June 30; the results obtained at that time did not differ from those of a month earlier except that on the whole smaller amounts of ammonia were present. In presenting the results it is convenient to separate the observations made in deep water where the stability of the water column preserves its heterogeneity from those obtained in shallow water and in the shallower channels across the banks where a high degree of turbulence prevails.

TABLE I

Stability of ammonia in stored sea water samples *

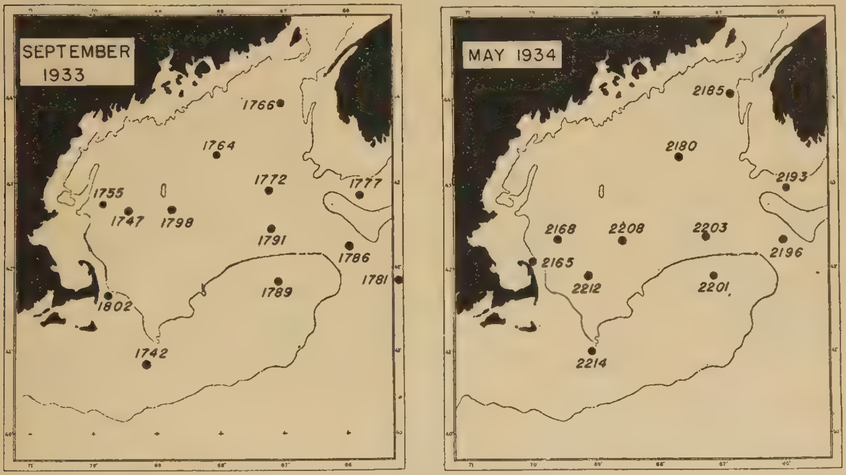
First analysis		Second analysis		Third analysis	
Hours after collection	NH_3-N, mg./M^3	Hours after collection	NH_3-N, mg./M^3	Hours after collection	NH_3-N, mg./M^3
1	40	7	41	290	10
2.5	27	8.5	19	290	8
3.0	35	7	35	290	15
2.5	28	8	30	290	2
4	20	—	—	90	13
4	62	17	54	90	45
6	42	—	—	90	25
6	44	18	24	—	—
6	57	18	46	90	37
5	49	17	28	90	23
4	46	17	32	—	—
5	42	18	30	90	20
†1.5	36	290	8		
†2	25	290	4		
†2.5	21	290	15		
†8.5	31	290	16		

* All values are averages from duplicate analyses.
† $HgCl_2$ added to sample at time of collection.

Observations in Deep Water

Figure 3 represents the concentrations of ammonia at various deep stations in September and in May. The stations are arranged as far as possible in the order of the positions through which the water is thought to circulate on penetrating the Gulf. Stations occupied in May are placed under stations occupied in comparable positions in September.

In September, Station 1781, 45 miles southeast of the Eastern Channel, showed the presence of some 10 mg. N per cubic meter in the upper 60 meters, diminishing to zero at 100 meters, below which level no ammonia was detected down to the depth of 2,000 meters. The ammonia in the water in the Eastern Channel was similar in distribution, there being none observable below 125 meters. Within the Gulf, on the other hand, the concentration of ammonia was distributed rather uniformly throughout the water column. The concentrations of ammonia occurring at any station increased towards the western basin of the Gulf, where amounts exceeding 50 mg. N per cubic meter were found.



Figs. 1 and 2. Position of stations at which distribution of ammonia was determined in September, 1933 and May, 1934 respectively.

In May the distribution of ammonia was very different. Amounts in excess of 10 mg. N per cubic meter were rarely observed in the upper 20 meters and at depths greater than 100 meters. Between these depths, at 30 to 60 meters, maximal concentrations occurred ranging in value from 10 mg. N per cubic meter in the Eastern Channel to 45 mg. N per cubic meter in the southern part of the western basin. In the following month similar conditions were observed save that the maximal concentrations did not exceed 25 mg. N per cubic meter.

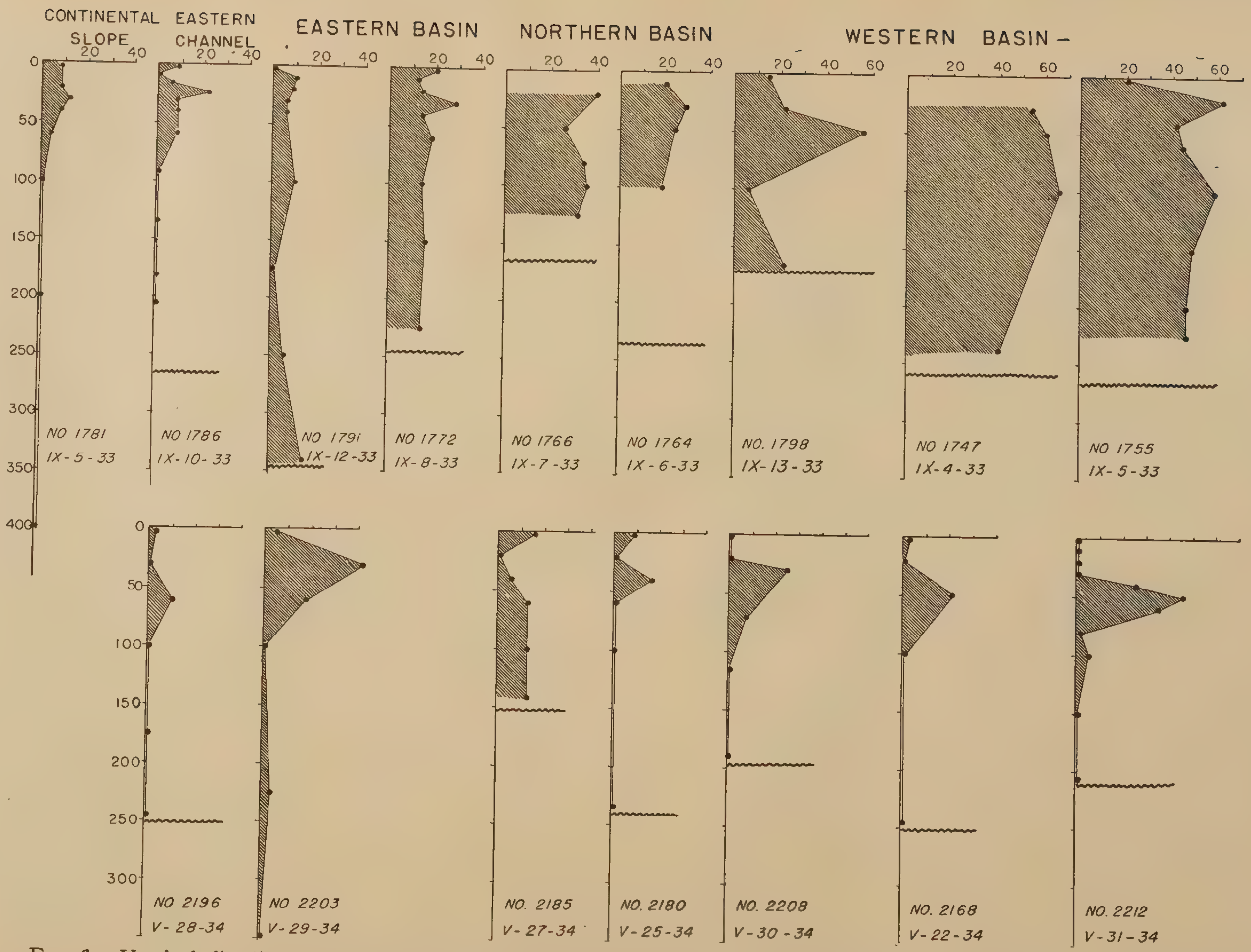


FIG. 3. Vertical distribution of ammonia in the deeper waters of the Gulf of Maine. Upper row, in September, 1933; lower row, comparable positions in May, 1934. Depths measured in meters downward along the ordinate. Concentrations of ammonia expressed as milligrams ammonia nitrogen per cubic meter along the abscissa.

Observations in Shallow Water

Figure 4 shows the distribution of ammonia at shallow stations off Cape Cod and on Georges Bank and in the strong tide ways of the South and North Channels. No definite difference in the seasonal picture is evident. In the channels considerable concentrations of ammonia occurred at all depths, though in May a maximal concentration a short distance below the surface was present in the North Channel. In the shallow stations the concentration sometimes increased with depth, sometimes the reverse.

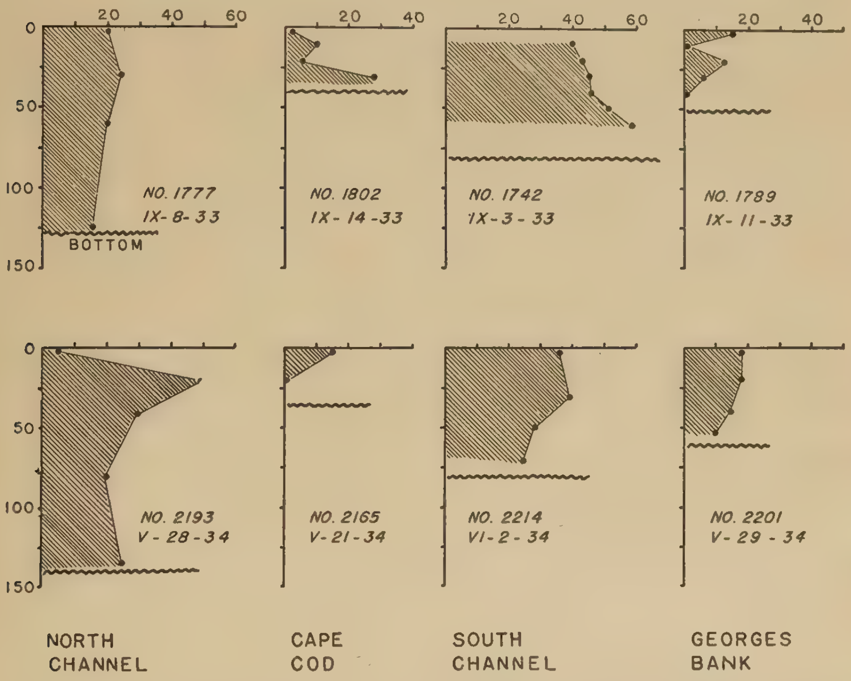


FIG. 4. Vertical distribution of ammonia in shallow waters of the Gulf of Maine. Upper row, in September, 1933; lower row, comparable positions in May, 1934. Concentrations of ammonia expressed as milligrams ammonia nitrogen per cubic meter along the abscissa.

Discussion

The distribution of ammonia appeared very irregular when the observations were first made. The magnitude of the concentrations of ammonia observed agreed well with the general range of observations made by earlier workers in various regions (Robinson and Wirth, 1934). It appeared, however, that great differences might be observed in similar situations at any time and in the same situation at different times.

In several ways our observations support the conclusions drawn from similar studies of ammonia in the English Channel made by Cooper (1933). He considers the formation of ammonia to be a "surface" phenomenon with lesser activity at the bottom. In the spring the surface concentrations decrease from utilization by phytoplankton. Our May observations would appear to be adequately explained on these assumptions. He also observed a general increase in summer and autumn, as did we in September.

As additional evidence has accumulated concerning the biology and chemistry of the Gulf, a number of correlations appeared which seem to give the findings additional significance.

Relation to Phosphate Cycle

The most striking difference between the occurrence of ammonia in September and in May is its relative abundance in the deep water at the end of summer compared with its absence there in the spring. This is precisely the relation found for another intermediate product of decomposition—dissolved, organic phosphorus compounds. These were found by Redfield, Smith and Ketchum (1937) to disappear from the water of the western basin in mid-winter and gradually to accumulate during the summer, reaching a maximum observed concentration in November. Like the ammonia in September, the concentration was quite uniform at all depths. In the spring these phosphorus compounds appear in the subsurface layers, as does the ammonia, before they may be detected in considerable quantity in the depths. It will be of interest to observe whether the ammonia does not almost entirely disappear from the water in mid-winter, as does the dissolved organic phosphorus.

Like the organic phosphorus, ammonia appears to accumulate at all depths in late summer. This should not be thought of as the accumulation of an inert product, however, for von Brand, Rakestraw, and Renn (1937) have shown, at least in a laboratory experiment, that the ammonia of decomposing plankton is nitrified completely in 30 days. It is probable that the ammonia is formed by decomposition throughout the water column, for in September there are no well-marked gradients of ammonia concentration which are necessary for its transport by eddy conductivity. There is no evidence, except in a few of the shallow stations, of increasing concentrations near the bottom, such as Seiwell (1931) observed in shallow bays and as might occur if decomposition on the sea bottom was responsible for a considerable part of the regeneration of nitrogen.

RELATION TO NITRITE

If the view to which Rakestraw (1936) has recently lent support is correct—that nitrite arises in the water through the oxidation of ammonia—one would expect a close correlation in the distribution of these nitrogen compounds. This expectation is in part fulfilled. The distribution of ammonia in May closely parallels that of nitrite, as shown in Fig. 5. Both may be explained through decomposition taking place in the subsurface waters. Rakestraw explains the absence of nitrite from the water immediately below the surface as being due to the assimilation of this substance by plankton. Evidently ammonia is similarly consumed. It is interesting, though not surprising, that there is no evidence that soluble organic phosphorus compounds are assimilated in a similar way—since they were found in as high concentration in the surface as at any depth.

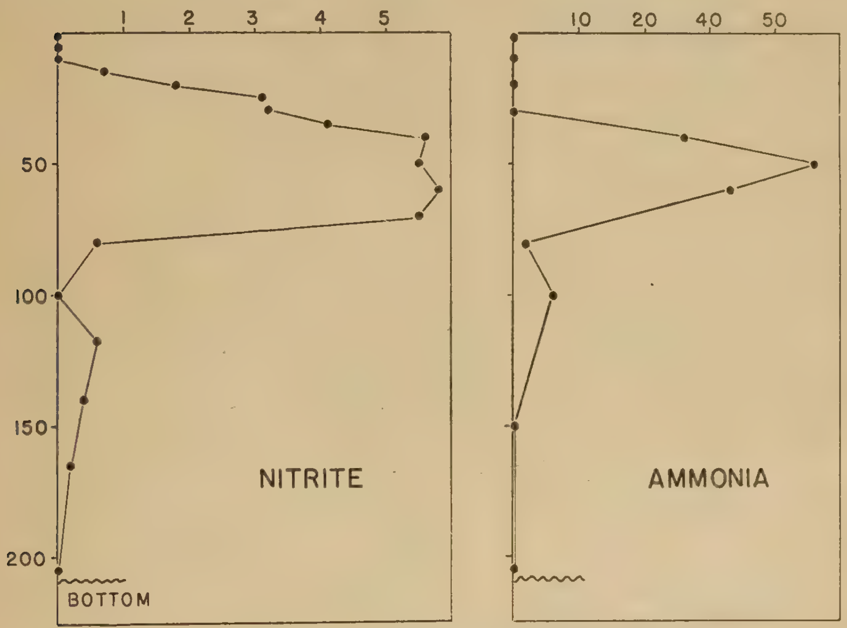


FIG. 5. Vertical distribution of nitrite and ammonia at Station 2212 May 31, 1934. Depths measured in meters downward along the ordinate. Concentrations measured in milligrams nitrogen present as nitrite or as ammonia per cubic meter.

Rakestraw remarks that the maximum for nitrite occurs between June and September. However, the nitrite does not appear to accumulate toward the end of summer to the extent to which ammonia and organic phosphorus compounds do. Nitrite is evidently a shorterlived link in the chain of nitrogen transformations than is ammonia for even in May the ammonia nitrogen concentration exceeds that of nitrite nitrogen by ten-fold.

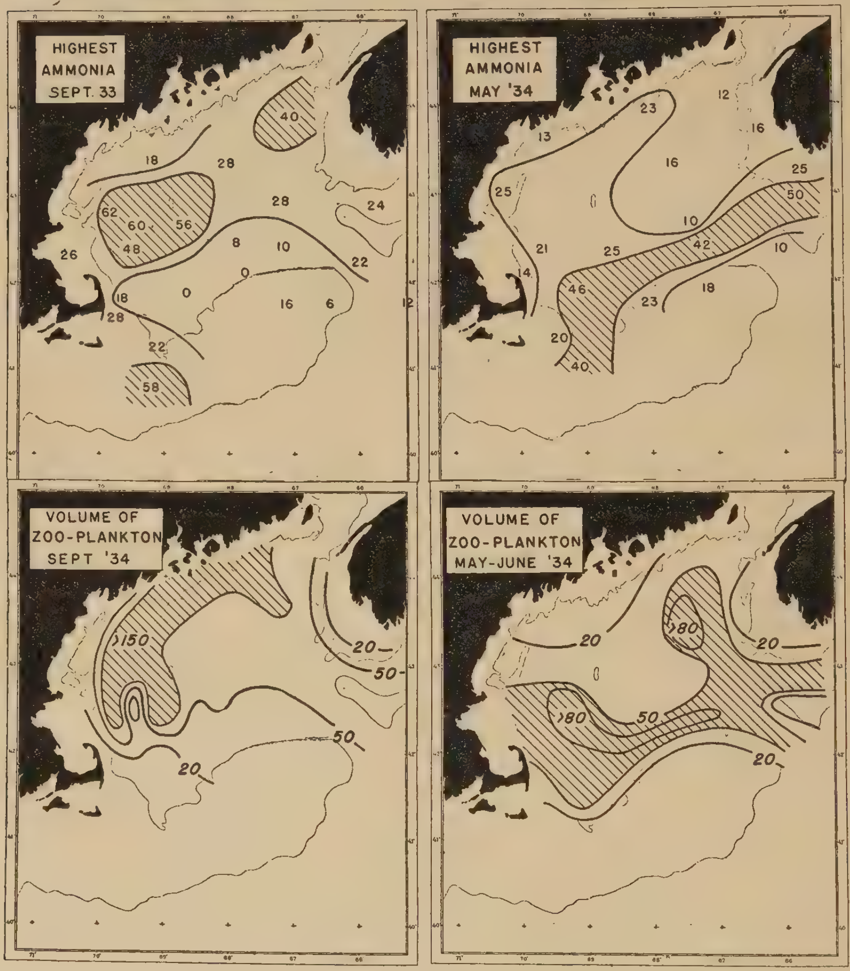

HIGHEST AMMONIA SEPT. 33
40
18
28
62
60
56
48
28
24
26
8
10
22
0
0
16
6
12
18
28
22
58
HIGHEST AMMONIA MAY '34
12
23
13
16
16
25
25
50
0
10
21
25
42
10
14
46
18
23
20
40
VOLUME OF ZOO-PLANKTON SEPT '34
>150
20
50
50
20
VOLUME OF ZOO-PLANKTON MAY-JUNE '34
>80
20
20
0
>80
50
20

FIG. 6. The highest concentration of ammonia in the upper 80 meters of water in various parts of the Gulf of Maine in September, 1933 and May, 1934 compared with the quantitative distribution of zoöplankton. Ammonia concentrations expressed in milligrams ammonia nitrogen per cubic meter. Zoöplankton volumes expressed as cubic centimeters of dry plankton per square meter of surface area caught in a vertical haul from near the bottom.

RELATION TO PLANKTON

The quantity of ammonia observed during both cruises varied greatly from station to station. In September the greater quantities were observed in the northern and western parts of the Gulf; in May in the southern and eastern regions. These facts did not assume significance until the plankton catches made at the time had been analyzed.

During each cruise a standard vertical zoöplankton haul was made at each station occupied (a number far exceeding those at which the ammonia was investigated). A 1.5-meter silk net was hauled from near the bottom to the surface. The total catch at each station was freed of excess moisture on a filter and its volume measured by displacement. The results of these measurements expressed as the volume of "dry" plankton per square meter surface have been plotted in Fig. 6 to show the general distribution of animal plankton. For comparison, the highest value of ammonia observed at each station in the upper 80 meters is also shown. While the correlation is not perfect, it is evident that the highest concentrations of ammonia at both periods of observation occur in regions in which the zoöplankton are densely distributed.

This correlation suggests that the animal plankton may be in some way responsible for the appearance of ammonia. While specific observations on plankton animals are lacking, ammonia appears to be the principal nitrogenous waste product of many invertebrate animals (Delauney, 1931). Harvey (1934) has pointed out that the phytoplankton community is continuously being grazed down by the zooplankton. These considerations point to the probability that zoöplankton, through their metabolic products and through their own decay, are an important intermediary in the liberation and distribution of ammonia in sea water.

Summary

1. In the deeper basins of the Gulf of Maine in May ammonia occurred in minimal concentrations at the surface and at all depths below sixty meters; maximal concentrations varying up to 45 mg. N per cubic meter occurred in a definite stratum between 30 and 60 meters.

2. In September the concentration of ammonia was rather uniform at all depths and increased as the distance from the open sea increased, concentrations exceeding 50 mg. N per cubic meter occurring in the western basin.

3. In the tideways of the North and South Channels, ammonia is distributed uniformly with depth in both May and September.

4. In shallow waters its occurrence showed no regularity.

5. The occurrence of ammonia may be correlated in part with the distribution of organic phosphorus compounds, of nitrite, and of

zoöplankton, so as to support the view that its distribution marks the place and the intensity of organic decomposition.

REFERENCES

von Brand, T., N. W. Rakestraw, and C. E. Renn, 1937. *Biol. Bull.*, **72**: 165.
Cooper, L. H. N., 1933. *Jour. Mar. Biol. Ass'n.*, **18**: 677.
Delauney, H., 1931. *Biol. Rev.*, **6**: 265.
Harvey, H. W., 1934. *Jour. Mar. Biol. Ass'n.*, **19**: 775.
Keys, A., E. H. Christensen, and A. Krogh, 1935. *Jour. Mar. Biol. Ass'n.*, **20**: 181.
Krogh, A., 1934. *Biol. Bull.*, **67**: 126.
Rakestraw, N. W., 1936. *Biol. Bull.*, **71**: 133.
Redfield, A. C., H. P. Smith and B. Ketchum, 1937. *Biol. Bull.*, **73**: 421.
Robinson, R. J., and H. E. Wirth, 1934. *Jour. Conseil. perm. int. pour l'explor. de la mer*, **9**: 15.
Seiwell, H. R., 1931. *Ecology*, **12**: 485.

Contribution No. 160

Reprinted from JOURNAL OF BACTERIOLOGY
Vol. 35, No. 5, May, 1938

DECOMPOSITION OF NITROGENOUS SUBSTANCES IN SEA WATER BY BACTERIA[1]

SELMAN A. WAKSMAN, MARGARET HOTCHKISS, CORNELIA L. CAREY AND Y. HARDMAN

Woods Hole Oceanographic Institution and New Jersey Agricultural Experiment Station

Received for publication October 22, 1937

It has been definitely established that organic nitrogenous bodies are rapidly decomposed in sea water by bacteria and that the nitrogen is liberated as ammonia. Waksman and Renn (1936) studied the oxidation of a series of amino acids in sea water using oxygen consumption as a measure of their destruction and found that, after making allowance for the basic sea water oxidation, the oxygen consumed in 5 days ranged from 50 per cent of the theoretical requirement for complete oxidation in the case of asparagine to 75 per cent in the case of glutamic acid. Measurements made at the same time showed that the increase in bacterial numbers ran parallel to the extent of the oxidation of the various amino compounds. In another experiment (Waksman, Carey, and Reuszer, 1933), it was calculated that in 19 days 1 gram of air-dry zooplankton liberated 100.7 mgm. carbon as CO_2 and 38.5 mgm. nitrogen as NH_3; the C–N ratio in the plankton was 4.57, whereas the corresponding ratio of the two metabolic products was 2.62. These results pointed to a very rapid liberation of the nitrogen as ammonia, in the decomposition of nitrogen-rich plankton, such as copepod plankton, by bacteria. In a third experiment it was found (Waksman and Carey, 1935) that the addition of 50 copepods (*Calanus finmarchicus*) to 225 cc. sea water resulted in an increase in bacterial numbers, in 24 hours, from 229,500 per cubic centimeter in the control water to 17,450,000 per 1 cc.; this was accompanied by an increase of 3.77 cc. in the consumption of oxygen per liter of water in 48 hours. These amounts were comparable to the decomposition figures for 4 mgm. asparagine in an equal amount of sea water.

---

[1] Contribution No. 160 of the Woods Hole Oceanographic Institution and Journal Series Paper of the New Jersey Agricultural Experiment Station, Department of Soil Microbiology.

The studies reported here examine in more detail the relationship between bacterial multiplication, oxygen consumption and nitrogen liberation, in the decomposition of nitrogenous material in sea water. Copepods were again used as representative of the nitrogen-rich marine zooplankton and asparagine as a type of nitrogenous organic compound.

The oxygen was determined by the Winkler method, the nitrate by the reduced strychnine method, the phosphate by the Atkins-Denigés method, and the bacteria by plate and microscopic methods. The ammonia was determined in the first experiment by the method of Krogh and in the other two experiments by Nessler's method.

In the first experiment (table 1) different numbers of fresh *Calanus finmarchicus* were added to a series of oxygen bottles containing freshly-taken sea water. The bottles were incubated, under water, in the dark and at room temperature, for a period of five days. Control bottles gave the decomposition figures for the basic metabolism of the sea water and of the sea water plus glucose, since the oxidation of glucose has been found to be a useful measure of the readily available nitrogen in sea water (Waksman and Carey, 1935). Other control bottles showed the decomposition figures for the sea water plus a nitrate source of nitrogen, with and without the addition of glucose as an extra source of carbon. According to this experiment, *Calanus finmarchicus* contains material readily decomposable by bacteria: a fact which was measured directly by determining the liberation of ammonia and phosphate and the consumption of oxygen, and indirectly by noting the increased oxygen consumption in those bottles which contained glucose.

From results presented in table 1, it is apparent that different amounts of copepod material apparently liberate nitrogen and

TABLE 1

Decomposition of Calanus finmarchicus by bacteria

NATURE OF MATERIAL			ANALYTICAL DATA					
Calanus per bottle*	Glucose	Nitrate nitrogen	Oxygen consumed		Bacteria in 1 cc.	Ammonia-N	Phosphate	Nitrate-N
			2 days	5 days	2 days	5 days	5 days	2 days
	mgm. per liter	*mgm. per liter*	*cc. per liter*	*cc. per liter*	*thousands*	*mgm. per liter*	*mgm. per liter*	*mgm. per liter*
0	0.0	0.0	0.36	0.54	151	0.02	0.045	0.01‡
0	0.0	0.07	0.30		180			0.08
2	0.0	0.0	0.66	1.08	285	0.08	0.06	
5	0.0	0.0	1.08	2.16	930	0.18	0.10	
15	0.0	0.0	2.01	3.78	1,950	0.31	0.15	
0	5.0	0.0	0.69	1.32	125			0.01
0	5.0	0.07	2.34	3.30	605			0.01‡
2	5.0	0.0	2.43	2.82	1,100			
5	5.0	0.0	2.49	3.64		0.09		
15	5.0	0.0	4.32	4.98†	950	0.22		

* 4.5 bottles to the liter.

† Oxygen completely used up.

‡ The same amounts found after 5 days.

phosphorus in the same ratio as the parallel figures show: for 2 copepods per bottle the ratio was,

$$\frac{\mathrm{N}}{\mathrm{PO_4}} = \frac{0.08 - 0.02}{0.06 - 0.045} = 4.0:1$$

for 5 copepods,

$$\frac{\mathrm{N}}{\mathrm{PO_4}} = \frac{0.18 - 0.02}{0.10 - 0.045} = 3.0:1$$

for 15 copepods,

$$\frac{\mathrm{N}}{\mathrm{PO_4}} = \frac{0.31 - 0.02}{0.15 - 0.045} = 2.8:1.$$

Orr (1933–34) has shown that it takes 3.5 to 10 grown *Calanus finmarchicus* to give 1 mgm. of dry material, and that the protein content of these copepods varies from 40 to 70 per cent for the males and for the females might be as much as 75 per cent. Assuming that a single copepod weighs 0.1 to 0.2 mgm. and that its cell substance contains 10 per cent nitrogen, one animal would contain 0.01 to 0.02 mgm. of nitrogen; nine copepods per liter of water,[2] on this assumption, would have contained 0.09 to 0.18 mgm. of nitrogen. The amounts of ammonia liberated in the above experiment are in accord with this theoretical nitrogen calculation; namely, 0.06 mgm. nitrogen was liberated as ammonia for an equivalent of nine copepods per liter (2 per bottle), 0.16 mgm. for two and a half times this number, and 0.29 mgm. for the largest quantity of copepod material, after subtracting the control. The corresponding amounts of oxygen consumed were, after allowing for the water control, 0.54, 1.62 and 3.24. In other words, both ammonia liberation and oxygen consumption were parallel to the number of copepods added to the bottles.

When glucose was added to the bottles, there was an increase in oxygen consumption of 1.50 cc. in the presence of 2 copepods, 2.32 cc. in the case of 5 copepods, and a larger amount with the highest number of copepods. When, in place of copepods, nitrate was added to the water containing glucose, at the rate of 0.07 mgm. nitrogen per liter, the increase in oxygen consumption was about the same as with 5 copepods. In other words, the bacteria consumed, for the oxidation of 5 mgm. glucose, 0.07 mgm. nitrogen as nitrate, which was transformed into bacterial protein. It is of special interest to note that when 5 mgm. of glucose were added to the water containing 5 copepods, the reduction in the amount of nitrogen liberated as ammonia was 0.09 mgm. per liter.

In another experiment it was found that the consumption of phosphorus by bacteria, using 5 mgm. of glucose, was equivalent to 0.06 mgm. phosphate. In other words, in the decomposition of glucose, the bacteria consumed 0.06 mgm. phosphate for the synthesis of their cell substance. The fact that the consumption of nitrogen, in the decomposition of 5 mgm. glucose, was 0.09 mgm. indicates that the ratio between nitrogen and phosphate requirements for bacterial metabolism in the sea is 1.5:1. Since the bacteria multiplied most rapidly under the conditions where oxygen consumption was greatest, and since the rate of multiplication and oxygen consumption was high where copepods were added, it seems beyond question that the bacteria can play an important part in the decomposition of animal plankton under natural conditions.

---

[2] Since each bottle contains 220 to 225 cc. water, 2 copepods per bottle will be equivalent to 9 per liter of water.

In two later experiments the decomposition of asparagine was studied in greater detail. In one of these experiments (table 2), oxygen consumption and bacterial multiplication in fresh sea water were compared with oxygen consumption and bacterial multiplication in the same water plus 5 mgm. asparagine per liter. A series of oxygen bottles was filled with each type of water; they were incubated in the dark and at room temperature under water, and, at frequent intervals, several bottles were removed for the determination of bacteria by the plate method and for chemical analysis. In both the control and the asparagine-enriched water, the greatest bacterial population was found in the one and two day incubation periods, and the rate of oxygen consumption was highest during the first four days of incubation. The asparagine-enriched water, at its peak, contained approximately five times as many bacteria per cubic centimeter and consumed, in four days, over twice as much oxygen. The high degree of oxygen consumption and bacterial multiplication indicate that the decomposition of practically all the asparagine used occurred in four days. The ammonia liberated was 60 to 70 per

TABLE 2

Decomposition of asparagine by bacteria in fresh sea water

PERIOD OF INCUBATION	SEA WATER			SEA WATER + ASPARAGINE, 5 MGM. PER LITER			
	Oxygen consumed	Bacteria in 1 cc.	Microscopic counts per field	Oxygen consumed	Bacteria in 1 cc.	Microscopic counts per field	$NH_3 - N$
days	*cc. per liter*	*thousands*		*cc. per liter*	*thousands*		*mgm. per liter*
1	0.46	656.0	54	1.31	3,340.0	125	
2	0.75	457.0	52	2.13	2,465.0	100	
4	1.19	16.0	30	2.84	53.5	49	
6	1.33	31.0		3.00	30.5		0.70
10	1.28	5.4		3.43	9.0		0.60

cent of the total nitrogen added in the form of asparagine. The excess oxygen consumption was 2.15 cc. in ten days. The theoretical amount of oxygen required to oxidize 5 mgm. of asparagine, with the liberation of nitrogen as ammonia, is 2.50 cc.; hence, only 86 per cent of the theoretical amount of oxygen was utilized in the oxidation of the asparagine; the rest of it presumably being consumed by the bacteria in 10 days for the synthesis of their cell substance.

TABLE 3

Decomposition of different amounts of asparagine in cultured sea water by bacteria

INCUBATION	CONTROL SEA WATER			SEA WATER + 5 MGM. ASPARAGINE PER LITER			SEA WATER + 10 MGM. ASPARAGINE PER LITER			SEA WATER + 20 MGM. ASPARAGINE PER LITER		
	Oxygen consumed	$NH_3 - N$	Bacteria in 1 cc.	Oxygen consumed	$NH_3 - N$	Bacteria in 1 cc.	Oxygen consumed	$NH_3 - N$	Bacteria in 1 cc.	Oxygen consumed	$NH_3 - N$	Bacteria in 1 cc.
days	*cc. per liter*	*mgm. per liter*	*thousands*	*cc. per liter*	*mgm. per liter*	*thousands*	*cc. per liter*	*mgm. per liter*	*thousands*	*cc. per liter*	*mgm. per liter*	*thousands*
1	0.10	0.01	54.0	0.78	0.50	520.0	0.42	0.13	410.0	0.33	0.06	435.0
2	0.16	0.01	345.0	1.58	0.65	2,515.0	2.97	0.85	2,900.0	4.55*	1.10	965.0†
3				2.09			3.36	1.20		5.36	1.70	
4	0.33	0.01	63.0	2.34	0.72	40.5	3.60	1.40	234.0	6.59	2.25	683.0
6	0.59	0.04	27.3	2.34	1.00	13.4	3.89	1.40	33.7	7.37	2.75	60.5
9				2.58	0.90	6.6	4.19		9.4	8.80	3.50	23.0

* Water transferred from oxygen bottles to clean, glass-stoppered bottle, shaken to resaturate with oxygen and returned to original bottles.

† Low oxygen tension unfavorable to aerobic bacteria.

Considerable oxygen is consumed by the bacteria in fresh sea water acting upon its organic matter, hence the water was allowed to reach a certain stability by holding it in the laboratory. A quantity of the fresh sea water was filtered through a No. 20 silk net and allowed to remain in an 18-liter glass bottle in the laboratory for 9 days. The water was then thoroughly aerated, in order to resaturate it with oxygen. This "cultured" water was divided into four lots, one of which was left unchanged, while to the other three lots were added respectively 5, 10 and 20 mgm. portions of asparagine per liter. The four lots were distributed in 225 cc. oxygen bottles and incubated under water, in the dark. Analyses were made at definite intervals, using duplicate or triplicate bottles.

The results, presented in table 3, point to the fact that asparagine is completely decomposed in sea water in 6 to 9 days, since in that time all the nitrogen in the asparagine became liberated as ammonia. There was also a rapid drop in bacterial numbers. Microscopic examination (table 4) revealed the fact that, after 9 days, most of the bacteria had disappeared leaving a mass of débris in which various protozoa abounded. Oxygen consumption slowed down considerably after 6 days, especially with the lower concentration of asparagine.

TABLE 4

Microscopic population of bacteria in sea water enriched with asparagine (table 3)

Number of cells per field

INCUBATION	CONTROL WATER	5 MGM. ASPARAGINE PER LITER	10 MGM. ASPARAGINE PER LITER	20 MGM. ASPARAGINE PER LITER
days				
1	12	34	39	69
2	48	124	96	79
3		28	43	44
4	10*	26	102	153
6	9	41	40	82
9		4	19	Débris

* One slide only, the other had very few bacteria.

The 20-mgm. amount of asparagine was at first oxidized slowly, but later was rapidly attacked by the bacteria so that, within 48 hours, the oxygen content in the water was reduced to a minimum. This produced an abnormal state for bacterial development, as could be demonstrated by the fact that the microscopic examination of the slides revealed the bacterial cells in a much swollen condition, resembling involution forms. The water in the remaining bottles containing the highest amount of asparagine was carefully transferred to clean glass-stoppered bottles; these were well shaken in order to resaturate the water with oxygen; the water was then transferred back to the original oxygen bottles, 3 to 4 drops of cultured water being used to close the glass seal. For a six-day period, 5 mgm. of asparagine increased the consumption of oxygen 1.75 cc. per liter; 10 mgm. of asparagine increased the consumption 3.30 cc. per liter, and 20 mgm. of asparagine 6.78 cc. per liter. The consumption of O_2 thus increased in exact proportion with the increase in asparagine. These results point to the fact that about 70 per cent of the theoretical requirement of oxygen for the complete oxidation of the asparagine was consumed by the bacteria in 6 days. The residual carbon was probably stored in the bacterial cell substance, in a manner similar to bacterial synthesis with glucose as a source of energy. The later oxygen consumption took place at the expense of these synthesized bacterial cells, which were rapidly disintegrated either by processes of autolysis or through consumption by protozoa.

In order to demonstrate microscopically the changes in the bacterial population in sea water and in water enriched with asparagine in the above experiments, two clean glass slides were placed in the oxygen bottles and examined microscopically, whenever the bottles were removed for analysis. The slides were air-dried, fixed 3 to 4 times in a flame, and stained for one minute in Hucker's crystal violet. The counts were made with an oil immersion lens. The fields measured 0.0082 square millimeter. All the bacteria were counted in five fields per slide and the averages for 10 fields (or 2 slides) reported.

The results obtained in the first experiment (table 2) show that plate and microscopic methods for the determination of bacteria present a similar picture; in both cases marked reductions in numbers were observed at 4 days incubation. While the plate method showed at that time a sudden dying off of the bacteria, the microscopic method, which does not distinguish between living and dead cells, did not show as rapid a reduction. However, after 6 days, the slides were covered with débris and the bacteria could no longer be counted.

Similar results were obtained in the second experiment (table 4). After a rapid rise, the numbers of bacteria rapidly decreased, so that after 9 days incubation, the cells could no longer be distinguished.

These results confirm those previously presented (Waksman and Hotchkiss, 1936) in showing that after a certain period the bacterial population in sea water will rapidly drop off in numbers. No matter how high the numbers become and no matter how the increase is brought about, it is soon followed by a rapid drop, due to autolytic processes and activities of the animal population.

SUMMARY

1. Copepods were rapidly decomposed in sea water by bacteria; this was accompanied by active bacterial multiplication, oxygen consumption, liberation of nitrogen as ammonia and phosphate regeneration.
2. Nitrogen liberation by bacteria in sea water, as measured by increased consumption of oxygen as a result of addition of glucose, gave equivalent values when measured directly as ammonia.
3. Seventy per cent of the theoretical amount of oxygen required to oxidize asparagine completely was consumed by the bacteria in 6 days, during the decomposition of the asparagine in sea water, and over 80 per cent in 10 days.
4. The bacterial maximum in incubated sea water or in water receiving asparagine was attained in 2 days, as determined by the plate method, and in 2 to 4 days, as determined by the microscope. This corresponded to the time of the maximum rate of asparagine decomposition.
5. The rise in bacterial numbers was followed by a sudden drop, after the nutrients added to the water had been exhausted. The drop was demonstrated by the plate method at an earlier incubation period than by the microscope.

The authors are indebted to Dr. C. E. Renn for making the ammonia determinations reported in table 1.

REFERENCES

Orr, A. P. 1933–1934 The biology of *Calanus finmarchicus*. IV. Seasonal changes in the weight and chemical composition in Loch Fyne. Jour. Mar. Biol. Assoc., **19**, 613–632.

Waksman, S. A., and Carey, C. L. 1935 Decomposition of organic matter in sea water by bacteria. II. Influence of addition of organic substances upon bacterial activities. Jour. Bact., **29**, 545–561.

Waksman, S. A., Carey, C. L., and Reuszer, H. W. 1933 Marine bacteria and their rôle in the cycle of life in the sea. Biol. Bull., **65**, 57-79.

Waksman, S. A., and Hotchkiss, M. 1937 Viability of bacteria in sea water. Jour. Bact., **33**, 389-400.

Waksman, S. A., and Renn, C. E. 1936 Decomposition of organic matter in sea water by bacteria. III. Factors influencing the rate of decomposition. Biol. Bull., **70**, 472 483.

Contribution No. 161

Reprinted from BIOLOGICAL BULLETIN, Vol. LXXIV, No. 1, 56–63, Feb., 1938
Printed in U. S. A.

THE ADSORPTION OF BACTERIA BY MARINE BOTTOM[1]

SELMAN A. WAKSMAN AND UNTO VARTIOVAARA

(*From the Woods Hole Oceanographic Institution and New Jersey Agricultural Experiment Station*)

In various recent studies (1, 4, 5) on the adsorption of bacteria in soil, the impression is left that the bacteria exert, in that state, only little effect upon the cycle of life in the soil. In his book on Agricultural Microbiology, Chudiakov (2) states emphatically that the problem of the condition of the bacteria in the soil hampered considerably a better understanding of soil microbiological processes. The existence of a surface relationship between the soil and microörganisms is true not only of bacteria but also of Protozoa, as shown by Cutler (3).

Different species of bacteria were found to behave differently in regard to their adsorption by the soil particles; their mobility and ability to form zoöglea seemed to be of special significance in this connection. The chemical activities of the bacteria, as measured by the evolution of CO_2, were considerably modified by the adsorption process (4). The finer soil constituents, namely the clay and silt fractions, were found to have a much greater adsorptive effect than the sand. Different soil types were found to adsorb bacteria to a different degree (5).

Rubentschik (8) made a detailed study of the phenomenon of bacterial adsorption in salt basins; the bacteria isolated from the mud were found to show a higher degree of adsorption than the bacteria found in the water. The conclusion was reached that the bacterial benthos consist of easily adsorbable species whereas the bacterial plankton contains organisms possessing a low degree of adsorption by the bottom sediments. A bacterial exchange took place in the mud, the adsorption of some species being accompanied by the desorption of others from the mud. The relative concentration of the bacteria, their nature and the type of bottom material exerted an influence upon the adsorption process. The activities of different species of bacteria were variously modified in the adsorbed state: the metabolism of some was lowered and that of others was increased.

---

[1] Contribution No. 161 of the Woods Hole Oceanographic Institution and Journal Series Paper of the New Jersey Agricultural Experiment Station, Department of Soil Microbiology.

According to Peele (6), the adsorption of bacteria is probably due to the attraction of unlike electric charges. The nature of the base in the soil complex influences considerably the process of adsorption, the monovalent cations showing the least adsorption.

In most of these studies, pure cultures of bacteria were used and the results obtained interpreted in terms of processes carried out by a complex population of microörganisms inhabiting the soil or the sea bottom. Usually a very short period of contact was allowed between the soil and the bacterial culture grown upon an artificial medium; no attempt was made to determine what happened after the culture had adjusted itself to the environment.

These studies have an important bearing upon the influence of the sea bottom upon the bacterial activities in the water. A number of questions may arise in this connection; 1. Is the specific occurrence of certain bacteria in the bottom due to their adsorption by the bottom material? 2. Is the relatively low number of bacteria in the sea water, as compared with that in the bottom, due to their removal from the water by the adsorption process? 3. Is this relationship responsible for the difference in the rate of bacterial processes taking place in shallow seas over a sand bottom such as Georges Bank, compared with the corresponding processes over a mud bottom, such as the Gulf of Maine (7, 11)?

These and other questions deserve fundamental treatment. No attempt will be made to give a definite answer in the following experiments, which must be considered as preliminary in nature.

EXPERIMENTAL

In order to eliminate the interfering effect of the bacterial population normally found in fresh bottom material, the first experiments were carried out with marine mud and sand which had been kept in a dry state for 5 years and in which the bacteria had been reduced to very low numbers.

In the first experiment, the adsorption of bacteria from a mixed population and from a pure culture of a marine bacterium by two different types of dry marine mud and sand was studied. A mixed culture was obtained by allowing fresh sea water to remain, in a glass container, in the laboratory, for a period of 48 hours. This resulted in an increase in the numbers of bacteria from a few hundred to 303,000 per 1 cc., as determined by the plate method. As a pure culture, a marine agar liquefying bacterium (No. 11) was used. This organism was selected because of the ease of recognizing the colonies produced on the plate. It had been isolated from sea water and kept in culture for a period of 2 years. The organism was grown in a medium poor in nutrients (1 gram peptone, 1 gram glucose and 0.5 gram K_2HPO_4 in one liter of sea water), for 24 or 48 hours. The culture was then diluted ten times with sea water sterilized by heating 30 minutes at 80° C. The two muds, No. 1329 and No. 1331, contained 2.46 and 1.58 per cent organic carbon and 0.28 and 0.16 per cent nitrogen, respectively (9). The sand contained 0.58 per cent carbon and 0.05 per cent nitrogen. Ten-gram portions of mud or sand were placed in 250-cc. flasks containing either 100 cc. cultured sea water or 100 cc. of the diluted 24-hour culture of the bacterium. The flasks were shaken by hand for 10 minutes, allowed to stand 10 minutes, and 1-cc. portions of the supernatant liquid plated out using a sea water agar medium (No. 1). The flasks were kept in the laboratory, with occasional shaking, and water plated out again after 2 and 21 hours.

TABLE I

Adsorption of bacteria from mixed and pure cultures by dry marine mud and sand

Nature of culture	Bacteria in 1 cc. water, thousands			
	Start	*10 minutes*	*2 hours*	*21 hours*
Cultured water				
Control	303	—	—	—
Plus mud 1329	—	28	13	3,700
Plus mud 1331	—	25	75	530
Plus sand	—	180	115	32,000
Bacterium No. 11				
Control	1,600	—	—	—
Plus mud 1329	—	9,620	6	5
Plus mud 1331	—	13,000	21	365
Plus sand	—	22,000	40,000	40,000

The results presented in Table I show that the pure culture of the bacterium was readily adsorbed by the marine mud. The sand, however, had no adsorptive effect; there was, in fact, a marked increase in bacterial numbers due to the separation of the bacterial masses or clumps into individual cells as a result of shaking with the sand. In the case of the crude cultures (i.e. the bacterial population in the cultured sea water), the immediate adsorption of the bacteria was followed by a rapid increase in numbers. The latter was due to the rapid multiplication of certain bacterial forms at the expense of the organic matter in the mud and sand.

This experiment was repeated and an attempt made to measure not only the multiplication of the bacteria, but also their activities, as influenced by the presence of bottom material. This could best be done by determining the oxygen absorption, as a result of bacterial multiplication (10). Two-gram portions of the two muds and 5-gram portions of the sand were placed in oxygen bottles of about 220 cc. capacity. The bottles were filled with 3-day-old cultured sea water. They were closed and incubated at room temperature, under water and in the dark. At different intervals, some of the bottles were removed and analyzed for bacteria, by plating out 1 cc. of the supernatant water, and for oxygen by the Winkler method.

The results reported in Table II show that there was comparatively little adsorption of bacteria from the mixed bacterial population in cultured sea water, by either marine mud or sand. On the contrary, there was a marked rise in bacterial numbers, reaching a peak in 17 to 42 hours, followed by a rapid decline. Active oxygen absorption took place in the bottles accompanying bacterial multiplication; this was due to the oxidation of the organic matter in the bottom material by the bacteria.

TABLE II

Influence of marine bottom material on the growth and metabolic activity of a bacterial sea water population

Nature of culture	Bacteria in 1 cc. water, thousands					
	Start	*3 hours*	*17 hours*	*42 hours*	*4 days*	*8 days*
Sea water control	0.5	0.9	1.2	1.0	7.3	3.1
Plus mud 1329	1.8	1.9	1,175.0	850.0	133.0	12.2
Plus mud 1331	1.9	1.7	1,240.0	1,435.0	205.0	3.3
Plus sand	2.2	3.9	1,255.0	615.0	65.0	3.3
	Oxygen consumed, cc. per liter					
	Start	*3 hours*	*17 hours*	*42 hours*	*4 days*	*8 days*
Sea water control	0.0	0.03	0.07	0.23	0.38	0.64
Plus mud 1329	0.0	0.25	0.73	1.42	2.53	3.48
Plus mud 1331	0.0	0.13	0.62	1.29	2.47	3.31
Plus sand	0.0	0.19	0.88	1.57	2.18	3.24

A study was now made of the adsorption of bacteria from mixed and pure cultures by the use of relatively large amounts of bottom material. In this experiment, the mud and sand were placed in large test tubes and sterilized by heat at 120° C. for 1 hour. Two volumes of cultured water, 2 days old, or two volumes of a diluted 2-day-old culture of No. 11 were added to the sterile tubes. These were now shaken for 1 minute and allowed to settle for 10 minutes. The supernatant liquid was plated out immediately. The tubes were then allowed to remain in the laboratory for 24 hours; some were shaken occasionally and some were left undisturbed. The water was plated out after 24 hours. The results (Table III) show that there was again a rapid adsorption of the bacteria from the pure culture by the mud but not by the sand. In the mixed culture there was at first a certain amount of adsorption of the bacteria; this was followed by a very rapid increase in numbers. The large amount of mud used offered a good source of energy, especially after heating, for many of the bacteria in the water.

A comparative study was now made of the adsorption of bacteria by fresh marine mud obtained from Buzzards Bay. Varying amounts of the fresh mud, containing 75 per cent moisture, were placed in 250-cc. Erlenmeyer flasks. Some flasks received 100 cc. portions of 2-day-old sea water, while other flasks received 100 cc. of a diluted 2-day-old culture of No. 11. All flasks were shaken for 1 minute, allowed to settle for 10 minutes and the supernatant liquid plated. This was repeated after 1, 2, 4 and 10 days. Some of the flasks were kept undisturbed, while others were shaken at various intervals. The plates were incubated at room temperature for 48 hours and counted.

TABLE III

Influence of shaking upon the adsorption of mixed and pure cultures of bacteria by sterile marine bottom material

Nature of culture	Bacteria in 1 cc. of surface water, thousands		
	Shaken		Unshaken
	Start	*24 hours*	*24 hours*
Cultured water control	4.6	153.0	170.0
Plus mud 1329	0.3	3,600.0	39,000.0
Plus mud 1331	0.1	12,000.0	22,000.0
Plus sand	100.0	10,000.0	7,000.0
Bacterium No. 11 * control	33,000.0	214,000.0	130,000.0
Plus mud 1329	3,300.0	4,400.0	31,000.0
Plus mud 1331	30.0	1.0	1.0
Plus sand	39,000.0	320,000.0	220,000.0
Bacterium No. 11 † control	13,000.0	21,000.0	21,000.0
Plus mud 1329	0.7	1.0	1.0
Plus mud 1331	30.0	1.0	1.0
Plus sand	18,000.0	18,000.0	25,000.0

* Dilution of culture with sterile sea water in ratio of 1 : 10.

† Dilution of culture in ratio of 1 : 30.

The results (Table IV) show that fresh marine mud exerted at first a reducing effect upon the numbers of bacteria in the mixed population.

After 24 hours, however, there were more bacteria in the water above the mud than in the control water sample. It is interesting to note that the larger the amount of mud used, the higher was the number of bacteria, especially in the shaken mud, in spite of the fact that the immediate reduction in numbers was greater with an increase in the amount of mud. This was due to the fact that the bacteria found in the mud a source of nutrients and began to multiply rapidly. This confirms the results obtained previously by the use of dry mud and sand.

In the case of the pure culture, there was active adsorption of the bacteria by the fresh marine mud, but here also the bacteria began to multiply after 24–48 hours. These were not, however, the typical colonies of the agar liquefying organism added to the mud, but various colonies of bacteria commonly found in the marine bottom.

TABLE IV

Adsorption of bacteria by fresh marine mud

Nature of culture	Fresh mud *	Shaking	Numbers of bacteria in 1 cc. water, thousands				
	grams per 100 cc.		*Start*	*24 hours*	*48 hours*	*4 days*	*10 days*
Cultured water	0	0	53	10	9	9	<1
Cultured water	2	0	44	17	4	3	<1
Cultured water	10	0	42	10	32	23	6
Cultured water	50	0	24	32	50	13	2
Cultured water	0	+	45	16	11	21	<1
Cultured water	2	+	30	13	27	29	17
Cultured water	10	+	33	16	23	36	62
Cultured water	50	+	23	13	21	79	80
No. 11	0	0	12,700	140,000	240,000	236,000	310,000
No. 11	2	0	11,900	23,000	3,000	2,500	58
No. 11	10	0	13,900	1,000	2,000	3,600	182
No. 11	50	0	17,900	5,900	6,000	1,800	41
No. 11	0	+	14,700	160,000	332,000	310,000	360,000
No. 11	2	+	16,600	67,000	23,000	6,700	160
No. 11	10	+	15,400	13,000	6,000	1,100	92
No. 11	50	+	15,000	4,400	1,000	68	104

* Moisture content of mud 75 per cent.

On the basis of these results, one can hardly conclude that the adsorptive action of the mud bottom upon bacteria in the water is detrimental in any manner to their activities. Even though mud adsorbs, removes, or inactivates a large number of bacterial cells such as may be obtained by growing a pure culture of a bacterium upon an artificial medium, there is still no proof that mud as such is in any manner injurious to bacterial processes in general, either those taking place in the water or in the mud itself. The evidence presented here seems to point merely to the fact that bottom mud exerts a certain controlling effect upon the nature of the bacterial population in the sea water. This is, of course, true of the bacteria found in the benthos or in the water immediately above it, but may not hold at all for the plankton bacteria found at great distances from the bottom.

The results of these experiments further emphasize the fact that the phenomena of adsorption obtained by the use of pure cultures of bacteria grown upon artificial media are difficult to interpret in terms of natural marine processes, since the conditions controlling the relations of the mud bottom to the natural mixed population of bacteria in sea water are much more complex.

SUMMARY

1. Marine mud exerted an adsorptive effect upon the bacteria in sea water. This effect was particularly evident when certain pure cultures of bacteria were added to the mud to give a heavy inoculation. Sand bottom had very little adsorptive action upon either mixed or pure cultures of bacteria.

2. In the case of the mixed bacterial population in the water, the adsorption of the bacteria by the mud was soon followed by a rapid increase of bacterial numbers; this took place at the expense of the organic matter in the bottom material.

3. These laboratory experiments showed that certain types of marine bottom material exerted a controlling effect on the numbers of bacteria, which were in intimate contact with them. There was no indication, however, of a permanent paralysis of bacterial growth or metabolism.

REFERENCES

1. Chudiakow, N. N., 1926. Über die Adsorption der Bakterien durch den Boden und den Einfluss derselben auf die mikrobiologischen Bodenprozesse. *Centbl. Bakt.*, II, **68**: 345.
2. Chudiakow, N. N., 1926. Agricultural Microbiology (Russian). Moskau. Page 214.
3. Cutler, D. W., 1919. Observations on soil protozoa. *Jour. Agr. Sci.*, **9**: 430.
4. Dianowa, E. W., and A. A. Woroschilowa, 1925. The adsorption of bacteria by soils and its influence upon microbiological activities. *Nautchno. Agr. Jour. Moscow*, **2**: 520.
5. Minenkow, A. R., 1929. Adsorption von Bakterien durch verschiedene Bodentypen. *Centbl. Bakt.*, II, **78**: 109.
6. Peele, T. C., 1936. Adsorption of bacteria by soils. *Mem.* 197, *Cornell Univ. Agr. Exp. Station.*
7. Reuszer, H. W., 1933. Marine bacteria and their rôle in the cycle of life in the sea. III. The distribution of bacteria in the ocean waters and muds about Cape Cod. *Biol. Bull.*, **65**: 80.
8. Rubentschik, L., M. B. Roisin, and F. M. Bieljansky, 1936. Adsorption of bacteria in salt lakes. *Jour. Bact.*, **32**: 11.

9. Waksman, S. A., 1933. On the distribution of organic matter in the sea bottom and the chemical nature and origin of marine humus. *Soil Sci.*, **36**: 125.
10. Waksman, S. A., and M. Hotchkiss, 1938. On the oxidation of the organic matter in the sea bottom. To be published.
11. Waksman, S. A., H. W. Reuszer, C. L. Carey, M. Hotchkiss, and C. E. Renn, 1933. Studies on the biology and chemistry of the Gulf of Maine. III. Bacteriological investigations of the sea water and marine bottoms. *Biol. Bull.*, **64**: 183.

Contribution No. 163

Quantitative Determination of the Nitrogen in the Particulate Matter of the Sea.

By

Theodor von Brand,
Woods Hole Oceanographic Institution, Woods Hole, Mass.[1])

Introduction.

THE principal steps in the nitrogen cycle in the sea are:— living organism, dead organism, ammonia, nitrite, nitrate, living organism. A thorough understanding of the circulation of nitrogen in the sea must be based upon the quantitative relationships involved in these various steps. So far, the soluble substances are the only ones which have received much attention, and during the last decade considerable information has been accumulated concerning their quantitative occurrence in various seas, seasonal fluctuations, etc. But the nitrogen fixed in the living and dead organisms floating in the oceans has been largely neglected, at least in so far as direct determinations are concerned. A start has been made, from a laboratory standpoint, to establish a relation between the nitrogen in soluble form and that in the particulate matter of sea water (von Brand, Rakestraw & Renn, 1937), but attempts to calculate the nitrogen occurring in organisms, from the soluble nitrate found before, and during, the flowering season of diatoms in the sea give results of doubtful value. The movements of water masses and the turnover of the organisms make it obviously impossible to determine the amount of nitrogen in the particulate matter in any part of the sea, at a given moment, from nitrate data taken at intervals of several weeks or months. Furthermore, conditions in this respect in the deeper water layers can certainly not be understood from the study of soluble substances alone; a direct determination of the nitrogen bound in the particulate matter is necessary. Since only limited amounts of water can be secured from the deeper layers, and since the amounts of particulate matter occurring there are very small, two difficulties have thus far made the direct approach difficult. One is the difficulty of getting the particulate matter out of the samples in a form suitable for analysis, and the second is the determination of such small amounts

---

1) Contribution No. 163 of the Woods Hole Oceanographic Institution.

of nitrogen with sufficient accuracy. In recent years these difficulties have been overcome. The methods, though not ideal, have now been tested sufficiently to warrant a review of them and of the results so far obtained. The following account includes previously published data, as well as new results obtained at Woods Hole during the summer of 1937.

Methods.

1. Securing the Samples.

The analytical methods have thus far not been adapted to use on board ship. The water samples must therefore be prepared in such a way as to preserve the particulate matter and avoid contamination as far as possible. In those parts of the sea so far investigated, the sample brought up in one ordinary Nansen bottle contains enough particulate nitrogen for duplicate analyses. The danger of contamination is less if the whole content of the water bottle is used exclusively for the nitrogen determinations, rather than an aliquot taken from several Nansen bottles. If other analyses are to be made at the same station, the water necessary for them should be taken from another water bottle fastened near the first one. The water sample should be emptied into the storage bottle (carefully cleaned and preferably glass stoppered), using a small amount to rinse it. Then 20 ml. of concentrated formalin are added and the bottle closed.

2. Concentration of the Particulate Matter.

Investigations in recent years have clearly demonstrated (Steemann Nielsen, Schmidt-Ries, 1936) that simple centrifugation is not sufficient for quantitative determinations of the nannoplankton. The method giving the most reliable results is Utermöhl's sedimentation method. His procedure, however, is for certain reasons not suitable for quantitative chemical work. The only other method giving similar results is the concentration method of Steemann Nielsen and v. Brand (1934). The principle is to precipitate calcium and magnesium hydroxides in the sea water by addition of alkali, which, by centrifugation, carry down the particulate matter quantitatively. The technical details of this method are as follows:— One litre of the sample is poured into a graduated cylinder of one litre capacity, after having cleaned both the cylinder and the neck of the bottle carefully. Then 5—10 ml. of a 5 per cent. KOH solution are added. The resulting precipitate is stirred thoroughly with a clean glass rod. It is essential that the precipitate be distributed completely through the whole water column. In my experience this is a point often neglected, and if not carried out properly large losses result. It seems not impossible that the unfavourable results reported by Bernard and Fage (1936) are due to the neglect of one of the minor details of the method. For this reason it is described here in greater detail than in the original communication. The graduated cylinder is covered with a clean watch-glass and the precipitate allowed to settle for 12 hours or more, during which time the sample should not be moved. After this, the level of the precipitate will be somewhere between the 50 and 100 ml. mark. The clear, supernatant liquid is then siphoned off. The siphon should not extend below the 200 ml. mark. When the level of the water has fallen to the 220 or 230 ml. mark, the siphon is carefully removed and the precipitate stirred. A few ml. of 5 per cent. HCl are added in order to reduce the amount of the precipitate. The exact amount of HCl is of no importance; the essential point is that the remaining precipitate should be voluminous enough to give the water a cloudy appearance after dispersion. The dispersed precipitate is transferred quantitatively into a centrifuge flask of 250 ml. capacity and centrifuged for about 5—10 minutes at high speed. The precipitate is then at the bottom of the flask in a compact gelatinous mass, from which the supernatant liquid can be poured off easily without loss of precipitate. Then enough HCl is added, drop by drop, to dissolve the precipitate completely, mixing with a clean glass rod meanwhile. The resultant clear solution is transferred quantitatively to a 50 ml. centrifuge tube and enough KOH solution is added to produce a precipitate again, in such a quantity that the solution is distinctly cloudy when thoroughly stirred. The centrifugation is repeated. The precipitate now contains all the particulate matter. The supernatant liquid is decanted into another centrifuge tube and KOH solution again added, as before. Another precipitate is obtained, similar to the first one, which is also separated by centrifugation, discarding the remaining solution. Although this second precipitate contains none of the particulate matter it is carried through the subsequent analysis along with the first one, as a control. It always contains a small amount of nitrogen, of unknown but non-particulate origin.

During the time the tubes and graduates are standing they are carefully covered with watch-glasses. Finally, both precipitates are suspended in "nitrogen-free" distilled water (see below), made up to the desired volume, and stirred. They are then ready for the actual analysis.

3. Nitrogen Analysis.

The method was originally proposed by Krogh and Keys (1934) for determination of the dissolved organic nitrogen in sea water. Its adaptation to the determination of the nitrogen content of particulate matter in the sea has been described by von Brand (1935), where details of the method will be found. It will be sufficient to describe here the general principles and to emphasize some points, which may appear unimportant at first glance, but which in my experience are essential for consistent results. The outline of the method is as follows:— The material to be analysed is heated to about 500°C. in a silver tube in the presence of alkali, but no oxygen, while passing through the tube a stream of hydrogen free from oxygen and ammonia. The organic nitrogen present in the particulate matter is transformed into ammonia which is determined according to the method of Teorell (1932) as modified by Krogh (1934). The hydrogen must be of high purity. Simple purification by bubbling it through sulphuric acid and passing it over heated copper proved to be sufficient for the hydrogen obtainable in Denmark. But "electrolytic" hydrogen, obtainable in the United States, gave high and very irregular blank values under these conditions. This could only be purified satisfactorily by passing it successively through one wash-bottle containing chromic acid, three of strongly alkaline permanganate solution, one of sulphuric acid, and finally over heated platinum gauze, a procedure similar to that used by Krogh and Keys (1934). The presence of impurities in the hydrogen is indicated by the permanganate solution turning green in a few days, after which it must, of course, be renewed.

I am in entire agreement with Krogh and Keys that one of the principal difficulties of the method is to get distilled water sufficiently pure. This must be used for the suspension of the precipitates before analysis, and to wash the inlet of the silver tube. Following Krogh's suggestion, I use deep sea water, which is first distilled directly, then again from strongly alkaline permanganate, and finally from dilute phosphoric acid. During the last distillation a stream of air, free from NH_3 and CO_2, is passed through the distillate. Such water gives blank values distinctly higher than distilled water prepared from tap water in Copenhagen. But since they proved to be consistent, this difference was not thought serious. The preparation of "nitrogen-free" water must, in any case, be given careful attention, but its source and preparation are questions which can only be answered in the light of local circumstances.

In the course of a routine analysis I always ignite 1 ml. of material (either from the sample of particulate matter or the "control" precipitate) and 1 ml. of water used for washing the inlet of the ignition tube. Since it is not convenient to bring the precipitates to exactly two ml., which are required for duplicate analyses, I use the following procedure:— The centrifuged precipitates have usually a volume between 0·3 and 0·5 ml. About 2 ml. of nitrogen-free water are added and, after stirring, duplicate analyses are carried out on 1 ml. portions. Finally the fluid remaining in the centrifuge tube is measured by sucking up into a graduated pipette, and the total amount of nitrogen in the precipitate is calculated. If there was too much nitrogen in the first samples for a satisfactory analysis, the small residue can be used for another determination.

4. Accuracy and Limitations of the Method.

The accuracy of the method is of course not as great as that of a macro-Kjeldahl determination. Duplicate determinations generally agree within 10 per cent., although somewhat greater differences may occur when very small amounts of nitrogen are present (von Brand, 1937).

A distinct drawback of the method is the fact that erratic results are obtained when there is so much nitrogen present that it completely exhausts the hypobromite used in the ammonia determination. There may, indeed, be little indication that this has taken place, and the apparent ammonia values will generally be lower, the higher the excess of ammonia. This danger was known to Teorell (1932). If there is any doubt about the validity of one determination, another one with a smaller amount of material, say half of it, should be performed. If it yields appreciably more than half, or even more than the whole amount of nitrogen found in the first determination, then this first one is incorrect, for too large a sample has been used. No general directions can, therefore, be given as to the amount of water to be used for the first precipitation, or, what amounts to the same thing, the amount of nitrogen-free water in which the material is finally suspended. Water samples of the following volumes, taken from the localities indicated, proved satisfactory for single analyses, using a hypobromite solution of twice the strength originally recommended by Krogh (1934): deep sea (lower depths), 500 to 1000 ml.; deep sea (upper depths), 250 ml.; Gulf of Maine, 100 to 200 ml.; water adjacent to Iceland, 20 to 200 ml.

The method of precipitation evidently carries down not only organisms, but all the material present in particulate form. Inevitably, it does not distinguish between the nitrogen of living organisms and that of detritus. This is unfortunate, but it must be kept in mind that the results of the analysis represent simply the nitrogen present in the particulate matter in a measured volume of water.

Results.

So far five deep stations have been investigated, the samples from all of them having been secured by the research vessel "Atlantis" of the Woods Hole Oceanographic Institution. The data from only one of these have so far been published (v. Brand, 1937). The stations represent different bodies of water: nos. 2639 and 2893, the Sargasso Sea; no. 2896, the Gulf Stream; no. 2894, slope water; and station 2809 the Caribbean Sea (Bartlett Deep). The nitrogen found in the particulate matter is shown in Table 1. It is evident that the greatest variations occur in the upper 400 metres. This is equally true whether comparison is made vertically at a single station or horizontally at different stations. The extreme values are 0·9 and 18 γ of nitrogen per litre ($1\gamma = \cdot 001$ mg.). Since 400 metres is generally recognized as about the limit of depth at which plant life is possible, it seems reasonable to assume that the differences found are due to differences in biological activity occurring there. Nevertheless, since a certain amount of detritus was probably present in all samples, it is impossible to attribute these differences solely to the varying amounts of organisms present. It is quite probable that a study of the seasonal variations at these stations would reveal still greater differences. Pronounced

Table 1.

Vertical Distribution of Nitrogen in the Particulate Matter.

Station 2639		Station 2893		Station 2894		Station 2896		Station 2809	
35° 08′ N. 66° 30′ W.		35° 30′ N. 67° 17′ W.		39° 06′ N. 70° 16′ W.		40° 15′ N. 65° 38′ W.		19° 06′ N. 80° 06′ W.	
VII/10-11/36		VII/12/37		VII/21/37		VII/29/37		III/1/37	
Depth m.	Nitrogen per l.	Depth m.	Nitrogen per l.	Depth m.	Nitrogen per l.	Depth m.	Nitrogen per l.	Depth m.	Nitrogen per l.
0	8·4	0	4·9	0	9·0	5	11·0	0	18·0
50	5·0	50	6·1	—	—	48	4·7	52	4·6
100	3·4	98	4·9	85	2·6	97	0·9	102	3·3
200	2·3	194	5·1	171	4·0	145	1·6	201	3·3
300	2·0	289	5·4	244	7·5	193	3·3	301	2·9
400	1·4	383	1·6	323	6·5	290	2·9	401	4·0
500	1·4	479	3·1	404	2·7	386	2·2	500	1·4
600	0	575	2·0	485	3·5	579	3·1	—	—
700	0·7	—	—	641	2·8	—	—	733	3·0
800	1·1	764	2·0	845	4·5	773	1·3	—	—
900	0·8	—	—	—	—	—	—	—	—
1000	1·6	1063	1·3	—	—	—	—	977	0·8
1100	0·2	1129	2·9	—	—	—	—	—	—
1200	0·2	—	—	—	—	1161	0·3	—	—
1300	0·3	—	—	1350	5·2	—	—	—	—
1400	1·6	1358	1·7	—	—	—	—	1463	1·5
1600	1·7	1603	2·3	—	—	1549	1·4	—	—
1800	2·9	1839	1·8	1856	3·8	—	—	—	—
2000	1·4	—	—	—	—	1976	1·4	1947	1·1
2250	2·8	2197	1·9	—	—	—	—	—	—
2500	0·5	2634	2·5	—	—	2472	1·3	2430	1·7
2750	0·8	—	—	—	—	2968	2·6	2910	1·3
3000	2·3	3345	1·8	—	—	3464	0·7	3490	2·0
—	—	3900	1·1	—	—	3960	1·5	3987	1·3
4500	0	4467	0·5	—	—	—	—	4484	1·5
4750	0	—	—	—	—	—	—	4980	2·8
—	—	—	—	—	—	—	—	5480	2·1
—	—	—	—	—	—	—	—	5979	3·0
—	—	—	—	—	—	—	—	6477	2·6

variations of the nitrogen bound up in organized matter would certainly be expected if such an investigation were carried out in the more fertile parts of the sea. It might be mentioned in this connexion that in the vicinity of Iceland values for the "particulate nitrogen" ranging from 10 to 73 γ per litre were found in the surface layers (0 to 50 metres) (v. Brand, 1935). According to a personal communication from Dr. E. Steemann Nielsen, who had collected these samples and studied their plankton, they were exceptionally free from detritus. It seems therefore probable that these values represent very nearly, at least, the amount of nitrogen bound in organisms. The fact that the values for particulate nitrogen in the Iceland water are higher than in any other waters so far investigated is in accordance with the well-known fact that plankton is much more abundant in northern waters than, for example, in the Sargasso Sea.

It is of some interest to compare the values for the upper layers of stations 2639 and 2893, since both these stations are very nearly at the same spot in the Sargasso Sea. Station 2639 was visited in 1936, and station 2893 in 1937. At the former, the particulate nitrogen decreased rapidly and quite regularly down to about 400 metres. At the latter no significant stratification was found in the upper 300 metres, but at 400 metres the nitrogen had dropped abruptly to about the same level as at station 2639. It is interesting to note that in 1936, at an unnumbered station (v. Brand 1937) in the slope water, a regular drop in particulate nitrogen, though with higher absolute values, was found similar to that at station 2639. In the corresponding layers of the slope water at station 2894, sampled in 1937, more or less irregular fluctuations were found. All these data are, of course, still too fragmentary to permit definite conclusions. They seem to indicate, however, that in the same parts of the sea noticeable differences in the distribution of the particulate matter occur from year to year. Apparently an investigation on a larger scale and over a longer period is desirable.

In the layers below 400 metres and down to about 4000 metres, the variations in the particulate nitrogen are much less pronounced than in the upper 400 metres. Practically identical amounts, between 1 and 3 γ per litre, were found in most of the deeper strata at stations 2639, 2809, 2893, and 2896. These values are markedly lower than those found in the upper layer. Both facts, the smaller degree of variation and the smaller absolute values, can be understood by considering the differences in living conditions in the two zones. Only in the upper layers is carbon assimilation possible. Depending upon local and seasonal conditions great differences in both the quantitative amount and qualitative composition of the nannoplankton may be expected there. In the deeper layers living conditions are in many respects much more uniform, resulting in relatively uniform nitrogen values. That these are low can be explained on the assumption that, with the possible exception of certain bacteria, no autotrophic organisms are present. Since Krogh (1934) has demonstrated that the dissolved organic nitrogen, which occurs in relatively large amounts in all layers of the sea, cannot be used to any noticeable degree by organisms, it appears that ultimately these must depend for their food upon other organisms dying in the surface layers and sinking downwards. Although of course the amount of such food substance coming down may vary widely, according to local and seasonal conditions, it can reasonably be expected that in the enormous deep sea spaces this turnover, passing through a series of stages of unknown duration, may eventually reach an equilibrium. Since the truly productive layers of the surface are very thin, in comparison with the physiologically unproductive space beneath, it is only natural that this equilibrium should result in small amounts of particulate matter in the latter zone.

A comparison of the data from below 4000 metres at stations 2639, 2893, and 2809 reveals a curious situation. In the two former, the Sargasso Sea stations, the lowest values of the whole water column occur in the deepest levels. In the samples taken from the Bartlett Deep, on the other hand, higher nitrogen values were found between 5000 and 6500 metres than between 1000 and 5000 metres (2 to 3 γ and 1 to 2 γ per litre, respectively). This difference may perhaps be explained on the assumption that in the relatively small and isolated Bartlett Deep the conditions for the accumulation of particulate matter, which possibly contains only a small percentage of living organisms, are more suitable than in the open sea. Other chemical analyses of samples from the Bartlett Deep (Rakestraw & Smith, 1937) have also shown the same kind of irregularity in the bottom layers, which may be due to very slow renewal of water here.

So far, the deeper layers of station 2894 (slope water) have not been mentioned. The particulate nitrogen here is distinctly higher than in the Sargasso Sea and the Caribbean, varying between 3 and 5 γ per litre. The reason for this peculiar behaviour is not clear. It may possibly be the result of a higher plankton content of the upper layers, although such a quantitative difference is not clearly indicated by the figures at hand. However, in the previous year the upper 300 metres of slope water yielded values about twice as high as those found in the Sargasso Sea. It must be kept in mind that changes occurring in the upper layers may be relatively rapid and will not necessarily be reflected in the corresponding deeper strata. It is also possible that the distribution of the particulate matter in the deeper layers is not only governed by the amount of dead matter sinking down from immediately above, but is also dependent upon organic matter which originated at some distant point and was carried in by the deeper currents. In other words, hydrographic factors will very likely prove important in the distribution of particulate nitrogen.

In addition to the deep stations, four others, in the shallower waters of the Gulf of Maine, have been investigated. Since the data for those have already been published (v. Brand, 1937), it will be sufficient to mention here only their chief characteristics. The nitrogen values were decidedly higher than in the open sea, from 10 to 34 γ per litre. The greatest amount was present in the upper 40 metres. Below this depth the values were fairly constant, between 10 and 17 γ per litre. A curious fact, as yet not entirely explained, was the observation that at all three of the stations which were deeper than 40 metres the lowest values occurred at intermediate depths, larger amounts being present in the deepest strata.

Discussion.

The nitrogen determined obviously belongs to nannoplankton organisms and organic detritus. Although it would be highly desirable to differentiate between these two factors, the only hope of doing so, even approximately, lies in the combination of chemical determinations and actual counts of the organisms present. In those rare cases in which one form is highly predominant, an effort might be made to culture it and then determine the nitrogen in a counted sample of pure organisms. A few determinations on pure cultures of diatoms (v. Brand, 1935) have shown that the nitrogen method is altogether suitable for this purpose, especially in cases in which the quantity of organisms available is too small for ordinary analytical methods.

The nitrogen determination itself, if handled properly and critically, yields values accurate enough to allow an attack on many problems heretofore considered inaccessible. So far only the very first steps have been taken, as this review has shown. Some of the more easily approachable problems may be mentioned briefly. It would be of great interest, for example, to extend the above studies to different seas and different seasons. The analyses reported for the waters near Iceland, in the Sargasso Sea, and in the Gulf of Maine already indicate that in different types of water different amounts of particulate matter occur. This might, of course, be anticipated from the known data for nannoplankton distribution. However, it would seem that the direct determination of the nitrogen in the particulate matter would corroborate the plankton counts and increase their significance considerably, in so far as the question of circulation of organic matter is concerned.

It is also possible that a more intensive study of the particulate matter would throw light on some hitherto unexplained peculiarities in the distribution of macroplankton in the deep sea. For example, Leavitt (1935) found that a minimum of macroplankton occurs in the Western Atlantic at a depth of about 1200 metres. It seems suggestive that at two of the three stations at which samples were obtained from these depths, a distinct minimum of particulate nitrogen was found. It is possible, though scarcely yet proven, that for some reason a minimum supply of food exists in this region, accounting for the scarcity of larger forms.

It may also be possible to study the nutrition of macroplankton organisms by means of this method. It should not be difficult to correlate the particulate nitrogen in a given mass of water with the number of macroplankton individuals, say copepods, and in that way perhaps clarify, to some extent, the food requirements of larger forms.

Finally, it might be possible to decide whether peculiarities in the distribution of particulate matter in the region of the oxygen minimum have any fundamental significance in connexion with this problem.

Summary.

Methods for the determination of the nitrogen in the particulate matter of the sea are reviewed, and the results obtained from such analyses are discussed.

Bibliography.

Bernard, F., and L. Fage, 1936, Recherches quantitatives sur le plancton méditerranéen. Bull. Inst. Océan. Monaco, No. 701.

v. Brand, Th., 1935. Methods for the determination of nitrogen and carbon in small amounts of plankton. Biol. Bull. 69: 221.

v. Brand, Th., 1937. Observations upon the nitrogen of the particulate matter in the sea. Biol. Bull. 67: 126.

v. Brand, Th., Rakestraw, N. W., and C. E. Renn, 1937. Experimental Decomposition and Regeneration of Nitrogenous Organic Matter in Sea Water. Biol. Bull. 72: 165.

Krogh, A., 1934. A method for the determination of ammonia in water and air. Biol. Bull. 67: 126.

Krogh, A., 1934. Conditions of life in the sea. Ecol. Mon. 4.

Krogh, A., and A. Keys, 1934. Methods for determination of dissolved organic carbon and nitrogen in sea water. Biol. Bull. 67: 132.

Leavitt, B., 1935. A quantitative study of the vertical distribution of the larger Zooplankton in deep water. Biol. Bull. 68: 115.

Rakestraw, N. W., and H. P. Smith, 1937. A contribution to the chemistry of the Caribbean and Cayman Seas. Bull. of the Bingham Oceanographic Collection, 4: Art. 1.

Schmidt-Ries, H., 1936. Grundsätzliches zur Zentrifugenmethode. Archiv f. Hydrobiologie 29: 553.

Steemann Nielsen, E. and Th. v. Brand, 1934. Quantitative Zentrifugenmethoden zur Planktonbestimmung. Rapp. et Proc.-Verb., Cons. Perm. Internat. Explor. de la Mer 89 (III): 99.

Teorell, T., 1932. Eine neue Methode zur titrimetrischen Bestimmung kleinster Mengen Ammoniak. Biochem. Zeitschr. 248: 246.

Contribution No. 165

ON THE OXIDATION OF ORGANIC MATTER IN MARINE SEDIMENTS BY BACTERIA

By

SELMAN A. WAKSMAN AND MARGARET HOTCHKISS

*Woods Hole Oceanographic Institution,**

New Jersey Agricultural Experiment Station
and

New York Medical College and Flower Hospital

The question as to whether the organic matter in the sea bottom is inert or is available as a nutrient for the bottom fauna and bottom-inhabiting bacteria is a problem of special interest in the cycle of life in the sea. A number of marine animals, making up the benthos or the bottom fauna, must depend upon this organic matter for their nutrition while the sea bottom also harbors an extensive bacterial population which require the energy to be derived from various nutrient elements for cell synthesis and respiration.

It has been definitely established that different marine sediments vary considerably in content of organic matter, depending on such factors as the nature of the bottom material, its distance from land, the topography of bottom, and the depth of water (*11*). Little is known as to whether this organic matter can be further decomposed once it has settled to the bottom. In his studies on the decomposition of Zostera plants in the sea, Boysen-Jensen (*4*) found that there was first a marked reduction in the nitrogen content to be followed later by a gradual increase in nitrogen. This led him to conclude that non-nitrogenous substances are decomposed to a greater extent than the nitrogenous matter by the bacteria in the sea bottom. The bottom fauna itself seemed to digest largely the non-nitrogenous bodies, such as the pentosans, while the nitrogenous compounds accumulated. The nitrogenous substances were considered to be transformed to humic compounds, which are attacked much less readily; and so the rôle of the bacteria in building up the complex organic nitrogenous compounds out of the mineralized forms of nitrogen was assumed to merit consideration. Boysen-Jensen separated the bottom sample into the "brown layer," or the uppermost 1 cm., and the lower 2 cm. layer; by digesting the sediment with pancreatic enzymes, he found that the upper layer of 120 sq. cm. surface of sea bottom contained 44–68 mg. of digestible

---

* Contribution No. 165 of the Woods Hole Oceanographic Institution, Journal Series Paper of the New Jersey Agricultural Experiment Station, and New York Medical College and Flower Hospital.

Reprint from SEARS FOUND. JOURN. MAR. RES.

nitrogen and the lower layer usually none. This method of determining how available the nitrogenous constituents of the sea bottom may be is open to criticism, because, under natural conditions, the digestion process is carried out by bacteria or by benthotic animals which will digest the carbohydrates even more readily and the small amounts of nitrogen consumed by these organisms would be built up into their cell bodies rather than be liberated in a mineralized form; a fact which was recognized by Boysen-Jensen.

From the bacteriological point of view, it is important first of all to determine to what extent bacteria are able to attack the humus complexes in the bottom material and how rapidly the essential nutritive elements, especially the nitrogen, are made again available for plant synthesis. The ratio of carbon to nitrogen in the marine humus has been found (*4, 11*) to be more or less constant, varying from 8:1 to 12:1. Under purely artificial conditions of decomposition, for instance when marine mud was air dried, remoistened and placed in a glass vessel, it was found (*11*) that 150 gm. of mud gave off, in 14 days, 55.8 mg. of CO_2 as carbon and 11.1 mg. of ammonia as nitrogen; this showed that the organic matter itself was not absolutely inert, but could be gradually, even if only very slowly, decomposed.

The above experiments carried out by the use of different methods, although artificial in nature, pointed definitely to the fact that the organic matter in the marine bottom is not absolutely inert but can be slowly made available. It remains to be determined to what extent this organic matter can undergo decomposition in a sea water system, by the natural bacterial population of the sea, and how this process affects the important elements carbon and nitrogen in the organic matter of the sea bottom.

Among the different methods used in studying the decomposition of small amounts of organic matter in sea water, the consumption of oxygen has been found to be most convenient (*12*). Therefore, it might be possible to utilize the rate of oxidation of the organic matter in the sea bottom as a measure of its availability. The application of this method to the study of certain types of bottom material, notably muds, is complicated by the fact that these can also absorb oxygen chemically. Moore, for example, observed (*9*) that there was an increase in the amount of immediate chemical absorption of oxygen by marine mud, to a depth of 5 cm.; but below that depth the chemical absorption of the oxygen became constant and amounted to 0.3–0.5 mg. of oxygen per 1 gm. of dry mud. He further stated that the biological oxygen absorption was slower, although no data were given to substantiate this. ZoBell and Anderson (*15*) reported that 1 gm. of dry mud absorbed from sea water 0.2–4.8 mg. oxygen in 6 hours, but biological absorption of oxygen continued at a slower rate almost indefinitely; both chemical and biological oxygen absorption were found to be much greater in the surface layers of mud than in the deeper layers. No details were given concerning the method for determining the biological absorption of oxygen, while in both contributions even the chemical absorption was only vaguely defined and described.

Various studies are on record concerning the absorption of oxygen by bottom material in lakes and in other bodies of water. Alsterberg (*2*) suggested that the disappearance of oxygen from the depth of a lake is due to the presence of easily oxidizable organic substances, often planktogenic in nature, in the bottom material. Kusnetzow (*7*) explained the disappearance of oxygen from the deeper portion of a lake as a result of the activities of the bacteria oxidizing methane, which had its origin in the anaerobic decomposition of the organic matter in the bottom material. He further reported (*8*) that the oxygen changes in a lake could be used as a measure of the intensity of the microbiological processes taking place in the bottom material.

Methods. The measurement of oxygen consumption has been of value in previous biological studies from this laboratory and it was decided that this method should be adapted to the present problem. In brief, this method consisted in the addition of the material to be studied to identical glass stoppered bottles which are incubated, usually submerged, at a predetermined temperature. At definite incubation times duplicate bottles were removed, the oxygen determined by the Winkler method, and the results expressed in cubic centimeters of oxygen per bottle. The bottles used in this work contained 225 cc. of liquid.

In attempting to use this method for the oxidation of marine bottom material, the method had to be variously modified: (1) It was necessary to compare the specific behavior of different types of bottom material. (2) It was desirable that the water in which the mud was suspended should be relatively inert and not exert too great an influence on the oxygen balance. (3) It was essential to determine how great an effect on oxygen consumption was exerted by the non-biological constituents of the bottom material. (4) The Winkler method being indirect, it was of prime importance to make sure that the results obtained were not due to chemical interactions of the reagents and the samples used.

The bottom material was obtained in a sterile glass tube which was lowered in a brass tube surrounded by a heavy weight; this is similar to the corer employed by Moore and Neill (*10*). The glass tubes with the mud cores were stoppered at each end with sterile rubber stoppers, kept on ice on the ship, and used as soon as possible after their return to the laboratory. The cores were carefully separated into two layers; the surface, brownish, freshly sedimented layer designated as the A horizon, and the sub-surface darker layer or B horizon. Quantities of mud varying from 0.1 to 0.5 gm., on a dry basis, were used; while for the sand 2 to 5 gm. portions were added to the 225 cc. bottles. The dry content of the material was calculated from a separate aliquot sample taken for moisture determination. The final results were recorded on the basis of one gram portions of dry material.

Although it was possible to use sea water newly procured as a menstruum in which to suspend the mud, the rapid oxygen consumption resulting from the oxidation of the organic matter in such sea water (*12*) might have been confused with the oxygen consumption due to the added bottom material. The sea water menstruum was therefore stabilized by ageing. This was accomplished by securing a quantity of water, taken from Woods Hole Harbor at a point distant from the pier, filtering it through a fine silk net (#20) and placing it in 18 liter glass bottles in the laboratory for at least 5 days. Before use the water was aerated to re-saturate with oxygen.

A series of experiments with sterilized and unsterilized material showed that there was very little oxygen consumption under aseptic conditions and gave ground for the belief that "chemical" oxidation was of little significance as compared with "biological." As a consequence, the containers with mud and water were placed under conditions favorable to bacterial activity. Room temperature was used, and oxygen determinations were made at the start and throughout the duration of the experiment, which was usually 5 to 15 days. When bacterial numbers were determined, by the plate method, a sample of water was usually taken above the settled bottom material.

After a few determinations had been made by adding the Winkler reagents directly to the bottles of water and mud or water and sand, it was apparent that the oxygen values obtained reflected an oxygen consumption in excess of the probable biological consumption. This was because the mud particles reacted with the iodine liberated. To eliminate this interference, the supernatant liquid was obtained by siphoning into smaller oxygen bottles (130 cc. capacity) and these were used for the oxygen determinations. It was found that siphoning did not interfere with the oxygen content of the water. The supernatant liquid from above the mud always gave a higher oxygen content than similar material which had not been freed of mud. The difference was sometimes as little as 0.03 cc. oxygen or as great as 0.19 cc. oxygen per bottle.

Experimental. In the course of the development of a standard method to be used in handling fresh bottom materials, data concerning several factors of interest in laboratory experiments on decomposition were gradually collected.

One of these preliminary experiments showed the extent of oxygen consumption which might be expected with dried material. Two dried mud samples, which had been previously obtained (*11*) from *Atlantis* stations 1329 and 1331 and found to contain 2.45 and 1.46 per cent organic carbon and 0.285 and 0.143 per cent nitrogen respectively, were studied. The oxygen consumption during 54 hours was compared with that of dry sand bottom from George's Bank containing 0.4 per cent carbon and 0.045 per cent nitrogen. The organic matter of both mud and sand was oxidized, although not very rapidly (Table I). In the case of sample 1329, 0.5 gm. of dry mud consumed 0.14 cc. oxygen, while 2 gm. of mud consumed 0.32 cc. oxygen in 54 hours. The corresponding amounts of oxygen consumed by mud 1331 were 0.12 and 0.32 cc. Although there was a difference in the organic matter content of the two muds, as shown by the carbon contents, there was very little difference in the rate of oxygen consumption. In the case of sand, however, much less oxygen was consumed: 2 gm. of sand absorbed, in 54 hours, 0.16 cc. oxygen; 5 gm. absorbed 0.31 cc.

TABLE I

OXIDATION OF DRY MARINE MUD AND SAND IN SEA WATER

Oxygen content of water, cc. per bottle

Mud Material	*Amount used*[1]	*Incubation, hours*			
	gm.	*0*	*6*	*30*	*54*
Water alone	—	1.21	1.19	1.16	1.15
1329 mud	0.5	1.20	1.18	1.10	1.01
1329 mud	2.0	1.14	1.13	0.99	0.83
1331 mud	0.5	1.18	1.16	1.09	1.03
1331 mud	2.0	1.12	1.12	0.96	0.83
Sand	2.0	1.20	1.20	1.08	0.99
Sand	5.0	1.24[2]	1.21	0.97	0.84

[1] Per 225 cc. oxygen bottle.

[2] Higher oxygen content above the control is due to a few small bubbles of air remaining in the sand.

TABLE II

INFLUENCE OF STERILIZATION UPON OXYGEN CONSUMPTION BY MARINE BOTTOM MATERIAL

Material[1]	*Oxygen, cc. per bottle*				*Bacterial control after 120 hours*
	Start 1 hr.	*18 hrs.*	*42 hrs.*	*120 hrs.*	
Standard sea water	1.07	1.08	1.07	—	—
+ 2 gm. mud 1331	0.99	0.96	0.92	—	—
Standard sea water	0.94	0.94	0.94	0.94	0
+ 3.75 gm. Gay Head sand	0.91	0.92	0.91	0.91	0
+ 1.47 sandy mud	0.94	0.92	0.91	0.88	0
+ 0.47 gm. mud	0.87	0.79	0.76	0.65	+

[1] Amounts calculated on dry basis.

While experiments under aseptic conditions showed that sterilized material absorbed only a very small amount of oxygen from the water (Table II), the biological oxygen absorption by the same samples presented a different picture. This is shown graphically in Figure 34. The sand used was from 22 meters depth, 1.5 miles W. by N. from Gay Head (Marthas

Vineyard); it had 24.9 per cent moisture. The sandy mud was obtained from a depth of 37 meters, near Buoy No. 4 LB, 7 miles S.W. of Gay Head; it had 26.4 per cent moisture. The mud came from Buzzards Bay, 1 mile N.E. of Gong 6; it was at a depth of 16 feet and had a moisture content of 71.0 per cent. Two gram portions of the moist sand and 0.5 gm. portions of the moist sandy mud and mud were used per 225 cc. oxygen bottles. Calculations were made on the basis of one gram of dry material. In thirty one days, 1 gm. of the sandy bottom containing 0.8% organic matter (calculated from the nitrogen content) absorbed 0.44 cc. oxygen; the sandy mud bottom containing 1.46% organic matter absorbed 1.31 cc. oxygen per gram; while the mud bottom with 5.82% organic matter absorbed 6.14 cc. oxygen per gram. The increases in oxygen consumption were greater than the increases in the organic matter content of the bottom material. This is shown by the ratio of oxygen in cc. to organic matter in mg., which was found to be 0.055 for the sand, 0.09 for the sandy mud, and 0.106 for the mud. The higher value for mud bottom points to the greater availability of its organic matter. Thus the degree of oxidation seems to depend on the presence of biological agents and the nature of the organic matter.

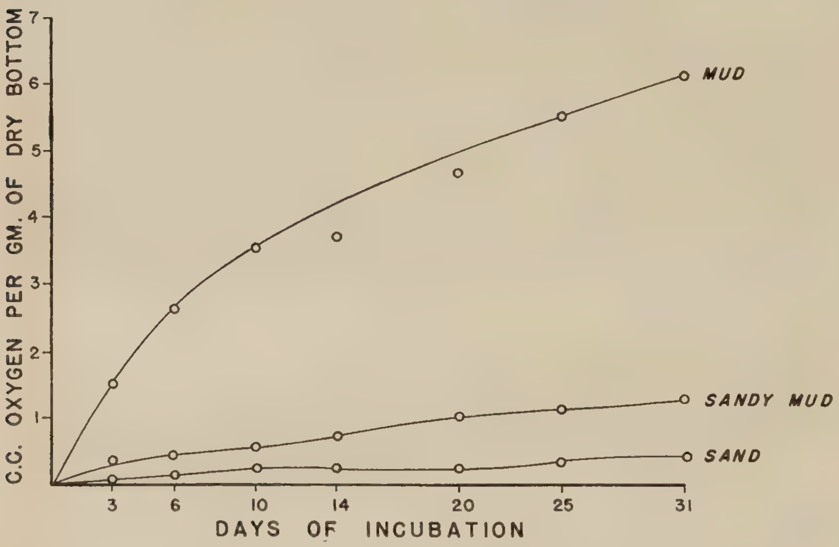


Figure 34. Course of oxygen consumption by different types of bottom material.

Some idea of the effect of different types of organic matter may be gained from a report on the experiments on oxygen absorption by material from different portions of the same core. Fresh cores of mud were obtained about

4 miles west by north of Gay Head. These cores were divided into 3 sections: 0–1 cm., 1–5 cm., and 5–20 cm. The moisture content of these sections of mud was 45.8, 33.7, and 26.7 per cent, respectively. One gram portions of the surface layer and 2 gm. portions of the lower layers of the fresh mud were added to a series of oxygen bottles; fresh sea water was used and the bottles were incubated for three days. The results presented in the following summary show that the surface layer of mud was somewhat more active biologically than the deeper layers, and this layer had the higher organic content.

Depth of layer cm.	*Mud used, dry basis gm.*	*Oxygen absorbed in 3 days cc.*	*Oxygen absorbed per 1 gm. of dry mud cc.*	*Nitrogen content of dry mud per cent*
0–1	0.54	0.17	0.315	0.095
1–5	1.32	0.35	0.265	0.087
5–20	1.47	0.40	0.272	0.070

In order to establish the relation of bacterial development to the oxidation of organic matter in the mud, the results of the following experiment may be cited. A mud core obtained in Buzzards Bay, near Weepecket Buoy, was divided into 3 sections. The upper layer of mud was suspended in some of the surface water and 5 cc. portions pipetted into a series of oxygen bottles; in the case of the other two layers 2 gm. portions of the moist material were used. The sea water menstruum was 24 hours old. There was a marked increase in bacterial activities in the water receiving marine mud. The surface layer of the mud was again the most active biologically. (Table III.)

TABLE III

Bacterial Multiplication and Oxygen Consumption of Different Layers of a Marine Mud Profile

Material used[1]	*0 days*		*1 day*		*5 days*		*Oxygen consumed per 1 gm. of dry mud*
	Bacteria in 1 cc.	*Oxygen, cc. per bottle*	*Bacteria in 1 cc.*	*Oxygen, cc. per bottle*	*Bacteria in 1 cc.*	*Oxygen, cc. per bottle*	
Standard sea water control	9,000	1.11	30,500	1.08	1,400	1.00	—
Standard sea water + 25 gm. dry mud 0–2 cm. deep[1]	4,000	0.95	83,000	0.74	19,800	0.49	1.84
Standard sea water + 1.05 gm. dry mud 2–6 cm. deep	7,500	0.80	114,500	0.68	15,800	0.31	0.47
Standard sea water + 1.05 gm. dry mud 6–10 cm. deep	5,500	0.85	116,000	0.69	9,700	0.19	0.63

[1] Nitrogen content of dry material, 0.146% for 0–2 cm., 0.180% for 2–6 cm., and 0.138% for 6–10 cm. layer.

A detailed study was made of the biological oxygen absorption by the A and B layers of a freshly taken mud profile. The position of the Station was off Gay Head. The A layer comprised the upper 2 cm. of mud and the B layer the lower 3 cm. (2–5 cm. depth). The nitrogen content of the mud was, on a dry basis, 0.176% for the A layer and 0.063 for the B layer. Cultured sea water was used and the oxygen determinations made in siphoned water. Different amounts of mud were added to the bottles. The curves presented in Fig. 35 are based upon the averages of the results obtained on the basis of 1 gm. portion of dry mud. The results again prove that the upper layer of mud exerts a greater oxygen absorption than the lower layer and that the process, although slow, is gradual and continuous. The greater oxygen absorption by the mud from the upper layer may be due, in this case as well, to the greater organic matter content.

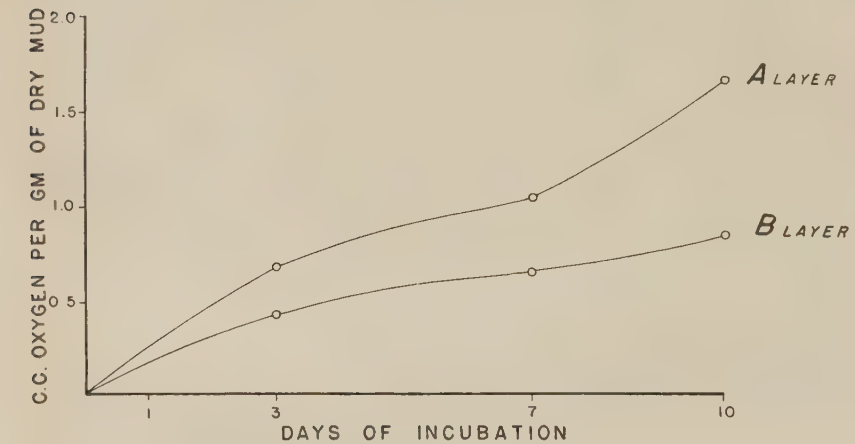


Figure 35. Course of oxygen absorption by surface (A) and sub-surface (B) layers of a Gay Head mud core.

In order to demonstrate further the biological nature of the oxidation process taking place in marine bottom material added to sea water, a study was made of the influence of temperature upon oxygen consumption. Cultured water, 3 weeks old, and fresh mud taken off the coast of Cape Cod, in line of Provincetown were used. This mud contained 0.234% nitrogen, on a dry basis. Five cc. portions of a suspension of mud in sea water, equivalent to 0.26 gm. of dry mud, were added to a series of oxygen bottles. These were filled with cultured sea water and incubated, under water, at 3 different temperatures: the lowest, or refrigerator temperature, ranged, after the first 24 hours, from 2° to 6° C., with an average of 4° C.;

the medium or room temperature, ranged from 21° C. to 25° C., average 23° C.; the highest, or incubator temperature, was quite constant, after 48 hours, ranging from 31.0° C. to 31.9° C., averaging 31.5° C.

The results (Table IV) show the increase in oxygen consumption effected by the higher temperature of incubation, at which temperature, there was comparatively little oxygen consumed after 10 days and very few bacteria left in the water after 15 days. At the low temperature, there was an extensive population of bacteria in the water containing the mud, but these bacteria had a low oxygen-absorbing capacity.

TABLE IV

INFLUENCE OF TEMPERATURE UPON THE OXYGEN CONSUMPTION OF MARINE MUD

Temperature of incubation	*Period of incubation*	*Oxygen consumed, cc.*			*Bacteria in 1 cc. water (+ mud)*
		per bottle		*per 1 gm. of dry mud*	
		water alone	*water + mud*		
°C.	*days*				
4° C.	5	0	0.05	0.19	528,000
4° C.	10	—	0.15	0.48	—
4° C.	15	0.05	0.21	0.62	49,200
23° C.	5	0.04	0.24	0.77	182,000
23° C.	10	—	0.34	1.00	—
23° C.	15	0.12	0.47	1.35	4,200
31.5° C.	5	0.10	0.33	0.89	382,000
31.5° C.	10	—	0.49	1.49	—
31.5° C.	15	0.11	0.52	1.58	<100

It was found in this, as well as in other experiments, that when a rise in bacterial numbers accompanying active oxidation of organic matter in water or in bottom material is followed by a rapid drop in numbers, oxygen consumption continues, although at a slower rate, in the presence of the few bacteria capable of developing on an agar plate. Similar observations have been made by Allgeier, Peterson, Juday and Birge (*1*) who found, in the case of lake sediments, that after gas evolution had reached a maximum, during the anaerobic decomposition of these sediments, bacterial numbers diminished rapidly; this drop was not accompanied by any marked decrease in gas evolution. This continued oxidation, after bacterial numbers have been markedly reduced, may be due to the continued action of bacterial enzymes or activating factors, as suggested by Kreps (*3*), who emphasized that bottom deposits are particularly rich in such enzymes. It may also be due to the controlling effect upon the bacterial population by the animal population in the water, as suggested elsewhere (*13*). Of interest in this connection is the work of Butterfield (*6*) who found that in the presence of certain protozoa, a decline in bacteria took place, not accompanied, however, by a diminution in the oxygen consumption in the water.

What is the greatest oxygen consumption which can be obtained with fresh marine mud under optimum laboratory conditions? It seemed possible to determine this if a new supply of aerated water was used to replace the sample removed by siphon for oxygen determination. A series of oxygen bottles received 1.0, 2.5, and 5.0 gm. portions of fresh marine mud. One series of bottles was placed in the dark under water, in an undisturbed state, while the bottles in the other series were shaken for a half minute, by hand, several times daily. At intervals of 1 to 4 days, the supernatent clear water was siphoned off and analyzed for oxygen. The bottles were immediately refilled with fresh cultured water, which had been saturated with oxygen, and incubated longer. The mud was obtained from Buzzards Bay, near Weepecket and contained 47 per cent moisture. The nitrogen content of the dry mud was 0.210%. The results reported in Table V represent the differences between the water controls and the water receiving the different amounts of mud. The total oxygen consumption per 1 gm. of dry mud, for a period of 28–30 days, was found to decrease with the amount of mud used; it amounted to 4.0 cc. when 1 gm. of moist mud was used per bottle; 3.99 cc. for 2.5 gm. mud, and 2.62 cc. for 5.0 gm. mud. Although the mud exerted a certain adsorptive effect upon the bacteria in the water, the numbers of bacteria were usually much higher in the water with mud than in the water alone.

TABLE V

MAXIMUM OXYGEN CONSUMPTION OF FRESH MARINE MUD UNDISTURBED AND RE-SUSPENDED

Incubation days	*Oxygen consumed per bottle*						*Bacteria in 1 cc. of water*[3]	
	Bottles shaken			*Bottles unshaken*				
Amount of mud used per bottle[1]	*1 gm.*	*2.5 gm.*	*5 gm.*	*1 gm.*	*2.5 gm.*	*5 gm.*	*0*	*1 gm.*
1	0.53	0.79	1.08	0.30	0.43	0.51	51,200	279,000
3	0.51	0.76	0.95	0.29	0.32	0.32	51,900	89,500
5	0.24	0.49	0.57	0.31	0.48	0.49	—	—
10	0.42	1.12	1.30	0.64	1.26	1.51	56,900	161,000
15	0.14	0.65	0.74	0.28	0.70	0.88	—	—
22	0.18	1.08	1.09	0.27	1.01	1.51	12,500	12,000
30	0.03[2]	0.60	1.41	0.09	0.87	1.55		
Total	2.05[2]	5.49	7.14	2.18	5.09	6.77		

[1] Moisture content of fresh mud 47%.

[2] 26 days incubation.

[3] In supernatant water above the mud.

A detailed study was now made of the oxidation of various types of bottom material collected from different depths of the sea and at different distances from land. Usually not over 7 days elapsed before taking the samples and subjecting them to oxidation in cultured sea water. Soon after the cores were obtained, they were placed, in an undisturbed position on ice. When brought to the laboratory, the cores were removed aseptically from the glass tubes, and divided into two portions: the upper 1 to 4 cm. or A layer and the lower or B layer, the latter varying from 4 to 25 cm. in thickness. Aliquot portions of the bottom material were placed in oxygen bottles; these were filled with cultured water, 7–15 days old, and the bottles incubated at room temperature in the dark and under water. Usually 5 bottles were employed for each sample: one bottle was analyzed immediately after the sediment had settled for 1–2 hours; 2 bottles were analyzed after 4–7 days and the other two after 8–15 days; only the results of the final analyses are reported in the tables.

TABLE VI

Oxygen Consumption by Bottom Material in the Neighborhood of Woods Hole

On basis of dry material

Sta.	*Position of station*	*Depth of station*	*Layer*	*Nitrogen*	*Oxygen consumed, cc. per 1 gm. in 4 days*
		meters		%	
1	Gay Head, 5¼ mile W by S	36.0	A	0.086	0.42
		36.0	B	0.070	0.29
2	Gay Head, ½ mile SE of Sta. 1	38.0	A	0.080	—
		38.0	B	0.067	0.18
3	Buzzards Bay 2 miles WNW of Weepecket Rock	15.7	A	0.257	1.10
		15.7	B	0.221	0.80
4	Same as 3, 1 mile NWW of Weepecket Rock	16.0	A	0.227	1.14
		16.0	B	0.182	0.93
5	Same as 3, 1/3 mile N of Weepecket Rock	15.3	A	0.255	0.82
		15.3	B	0.222	0.87
6	Same as 3, 1 mile NE of Gong 6	16.0	A	0.259	1.04
		16.0	B	0.222	0.94
7	Same as 3, Buoy 4LB	37.0	A	0.085	0.13
		37.0	B	0.048	0.05

In the first experiment (Table VI), a group of bottom samples were collected from stations in the neighborhood of Woods Hole; the water was 7 days old, and the oxidation period only 4 days. In making the calculations, allowance was made for the chemical oxidation or oxygen consumption within 1 to 2 hours, and oxygen consumption by the water controls. The results reported in this and other tables thus represent the biological oxygen consumption due to the oxidation of the bottom material in the water; they are reported on the basis of 1 gm. of dry material. A marked correlation was found between oxygen consumption and organic matter content of the bottom material. The cores from stations 3–6 are higher in organic matter and show also more active oxygen consumption. By comparing the average organic matter content of these stations with those containing less organic matter, using the results for the two layers, one finds that the organic matter in the former oxidizes more readily than in the latter.

Station Nos.	*Organic matter content*	*Oxygen consumed, cc. per liter*	*cc. of oxygen / mg. of organic matter*
	%		
3–6	4.50	0.95	0.0210
1, 2, 7	1.45	0.21	0.0145

In the following two experiments, bottom samples were obtained at varying distances from land. In the first Atlantis cruise, the depths of the stations ranged from 104 meters to 1,250 meters. With the exception of the shallow station, coming from a depth of 104 meters, the organic matter from these bottom samples showed comparatively little oxygen consumption (Table VII). Although the organic matter content of these bottom samples was about 2 to 3 per cent, as calculated from the total nitrogen, there was only 0.07–0.27 cc. oxygen consumed per 1 gm. of dry material, in 14 days. These results suggest that the organic matter in the sea bottom at greater distances from land has a considerable resistance to decomposition. This was found to hold true of the oxidation of the organic matter in the bottom samples obtained on the second cruise of the Atlantis, when the samples came from even greater depths. The highest oxidation was 0.59 cc. per 1 gm. of dry bottom material, although this material contained 2.5 per cent organic matter. These results thus point definitely to the lower oxidizability of the organic matter in the deep sea bottoms.

A comparison of the data for the deeper stations, presented in Tables VII and VIII with those of the shallower stations (Table VI) points to another interesting difference: in the case of the bottom samples close to land, the upper layer of the bottom material gave greater oxygen consumption than the lower layer; however, in the case of the deeper stations (7, 8, 9 in Table VIII), the lower layer of bottom material frequently showed as great if not greater oxygen consumption than the upper layer.

In order to study further the oxidizability of the organic matter in sea bottom not far distant from land 3 groups of stations were selected as representing characteristic differences in depth and position. One group (stations 1–8) was obtained in line of the Isles of Shoals; the other group (stations 9–13) came from the 99 fathom hole in Massachusetts Bay, and the third group (stations 14–17) from a line off Provincetown. The results, presented in Table IX, show that the consumption of oxygen or the decomposibility of these bottom samples was greater than in the case of the bottom material which had been obtained at greater distances from land. There was also a certain definite correlation between the rate of oxidation and the depth or position of the bottom material which is brought out in the group of samples from the 99 fathom hole (stations 9–13). In this hole the deeper stations gave higher organic matter content and the oxygen consumption by the bottom material was greater. A certain correlation was also found between the amount of organic matter in the bottom material and the rate of its oxidation.

TABLE VII

OXYGEN CONSUMPTION BY BOTTOM SAMPLES FROM FIRST "ATLANTIS" CRUISE

On basis of dry material

Sta. No.	*Position of station*	*Depth of station*	*Layer*	*Nitrogen*	*Oxygen consumed, cc. per 1 gm. in 14 days*
	W Lat. N Long.	*meters*		%	
1	40.04′ x 70.50′	104	A	0.191	0.63
		104	B	0.154	0.65
2	39.56′ x 70.49′	175	A	0.046	0.10
		175	B	0.048	0.07
3	39.52′ x 70.48′	600	A	0.105	0.13
		600	B	0.087	0.15
4	39.50′ x 70.46′	914	A	0.106	0.07
		914	B	0.102	0.08
5	39.48′ x 70.47′	1,250	A	0.154	0.27
		1,250	B	0.139	0.17

TABLE VIII

OXYGEN CONSUMPTION BY BOTTOM SAMPLES OBTAINED IN SECOND "ATLANTIS" CRUISE

On basis of dry material

Sta. No.	*Position of station*	*Depth of station*	*Layer*	*Nitrogen*	*Oxygen consumed, cc. per 1 gm. in 15 days*
	W Lat. N Long.	*meters*		%	
6	40.14′ x 67.46′	1,134	A	0.030	0.31
		1,134	B	0.040	0.08
7	40.13′ x 67.39′	1,609	A	0.130	0.26
		1,609	B	0.112	0.41
8	40.09′ x 67.23′	2,100	A	0.133	0.39
		2,100	B	0.124	0.59
9	40.04′ x 66.67′	2,967	A	0.118	0.27
		2,967	B	0.089	0.34
10	40.25′ x 66.00′	4,000	B	0.034	0.11

In all the above experiments, the water was tested, at the end of the oxidation period, for ammonia, nitrite and nitrate.[1] In no case could these be detected save in mere traces. This might have been due to the fact that the incubation period of 14–15 days was not sufficient for the liberation of the nitrogen in appreciable or detectable amounts in the decomposition of the mud. However, it emphasizes the fact that the nitrogen in the marine bottom is highly resistant and is not readily mineralized by the bacteria. Once the organic residues have settled to the bottom, the nitrogen has become so closely bound in an organic form as to be practically immune to microbial attack. Quite the opposite occurred in experiments on the decomposition of marine plankton (*5, 14*).

---

[1] The authors are indebted to Dr. Cornelia L. Carey for making these tests.

In one experiment (Table V), the mud was analyzed for total nitrogen at the beginning and at the end of the decomposition period. There was an increase, on the basis of the dry mud, from 0.210% nitrogen in the fresh

TABLE IX

OXYGEN CONSUMPTION BY BOTTOM MATERIAL FROM A LINE OF STATIONS OFF MASSACHUSETTS BAY, ISLE OF SHOALS AND CAPE COD

Sta. No.	*Position*	*Depth*	*Layer*	*Nitrogen*	*Oxygen consumed, cc. per 1 gm. in 14 days*
	W Lat. N Long.	*meters*		%	
1	42°57′ x 70°31′	83	A	0.193	1.54
		83	B	0.139	0.94
2	42°57′ x 70°27′	100	A	0.209	1.55
		100	B	0.173	1.49
3	42°57′ x 70°25′	100	A	0.138	0.97
		100	B	0.048	0.46
4	42°57′ x 70°22′	132	A	0.252	1.19
		132	B	0.192	2.02
5	42°57′ x 70°20′	157	A	0.291	1.23
		157	B	0.254	1.36
6	42°57′ x 70°18′	161	A	0.306	1.00
		161	B	0.272	1.24
7[1]	42°59′ x 70°15′	155	A	0.288	1.59
		155	B	0.227	1.32
8[2]	42°59′ x 70°12′	175	A	0.326	1.86
		175	B	0.278	1.06
9[3]	42°30′ x 70°18′	90	A	0.081	0.06
10	42°30′ x 70°18′	145	A	0.179	0.87
		145	B	0.051	0.47
11	42°30′ x 70°18′	170	A	0.162	0.83
		170	B	0.176	1.88
12	42°30′ x 70°18′	170	A	0.245	1.33
		170	B	0.211	1.45
13	42°30′ x 70°18′	175	A	0.245	1.71
		175	B	0.228	0.94
14	42°00′ x 69°46′	150	A	0.081	0.62
		150	B	0.047	0.72
15	41°59′ x 69°41′	195	A	0.260	1.41
		195	B	0.261	1.43
16[4]	42°01′ x 69°38′	210	A	0.233	1.11
		210	B	0.234	1.46
17[5]	42°01′ x 69°43′	165–170	A	0.226	1.04
		165–170	B	0.204	1.23

[1] Atlantis Station 2648. [2] Atlantis Station 2654.

[3] Stations 9–13 are from 99 fathom hole in Massachusetts Bay and close to it.

[4] Atlantis Sta. 2645. [5] Atlantis Sta. 2646.

mud to 0.233% nitrogen[1] in the mud left after 30 days' oxidation. If one is to assume that this increase in the nitrogen content of the mud is accompanied by a narrowing in the carbon-nitrogen ratio and, therefore, by a corresponding decrease in the carbon content, the amount of carbon lost by oxidation would correspond roughly to 2.3 mg. carbon per 1 gm. of dry mud oxidized. The amount of oxygen theoretically required for the oxidation of this carbon would be 4.29 cc. The actual oxygen consumption varied from 2.62 to 4.00 cc. oxygen, depending on the amount of mud inoculum, as shown above. This brings added proof that the nitrogen was not liberated in a mineralized form since it could be accounted for almost quantitatively in the residual mud.

DISCUSSION

A knowledge of the abundance, chemical nature and rapidity of decomposition of the organic matter in the sea bottom represents a number of significant theoretical and practical problems. Among these, the question of the influence of the nature of the organic matter upon the occurrence of bottom-feeding or benthotic animals, as well as the decomposition of the organic matter by bacteria and the return of the elements into circulation are not the least important. To what extent does the content of organic matter in the sea bottom influence the abundance of bottom feeding animals? Is the occurrence of the latter connected with the amount of organic matter or with the nature of this organic matter? Is the organic matter subject to decomposition or oxidation by bacteria, and how can this best be measured?

The determination of the organic matter content in the sea bottom represents little difficulty. It can be done roughly by measuring the loss on ignition, but more accurately by an analysis of the organic carbon or the total nitrogen content. Since the ratio between these two elements is more or less constant in the marine organic matter or marine humus, the determination of one of these two elements may be sufficient as a measure of the abundance of humus. The carbon can be multiplied roughly by 2 and nitrogen by 20, to give the total organic matter in the bottom material. A knowledge of the nature of the organic matter represents, however, a much more difficult problem. Chemical analyses, as attempted by one of us (*11*) or hydrolysis by means of proteolytic enzymes, as attempted by Boysen-Jensen (*4*), are either too complicated or are not comparable with marine processes. The measurement of the rapidity of oxidation of the bottom material, under conditions similar to those taking place in nature, namely in a sea water system with favorable oxygen tension, offers a much simpler method for comparing different types of marine bottom material. The oxidation of the organic matter in sea water was found to be a convenient method for measuring the relative availability or stability of this organic matter.

---

[1] The 3 samples of mud contained 0.230%, 0.238%, and 0.232% nitrogen.

Three of the stations from which material was collected for the present investigation have also been used the year previously in a study made by Dr. Hjort and Dr. Bigelow concerning the relation of sea bottom to the occurrence of shrimps. It is of interest to compare, for these 3 stations at least, the abundance of organic matter, the rate of oxidation and the occurrence of shrimps:

Sta. No.	*Shrimp catch (1936)*	*Nitrogen content of mud bottom, dry basis, per cent*		*Oxygen consumption cc./1 gm. in 14 days*
		(1936)	*(1937)*	
	qts.		*A layer*	
2645	1.5	0.217	0.233	1.11
2648	16.0	0.295	—	1.59
2654	180.0	0.309	0.326	1.86

The above results show a very interesting correlation between the occurrence of shrimps and the rapidity of oxidation of the organic matter in the bottom material. The number of samples used for this comparison is too small, to justify any broad conclusions; but the results are highly suggestive.

Of particular interest in connection with these studies is the fact that the organic matter in the sea bottom is oxidized only very slowly by bacteria. It was found that 1 mg. of organic matter consumed only 0.1 cc. oxygen, when allowed to oxidize, under optimum conditions in the laboratory, for a period of 15 to 30 days. Assuming 50 per cent carbon in the organic matter, only about 10 per cent is found to become oxidized in this period of time. When this is compared with the rapid decomposition of the plankton material (*5, 14*), the differences are particularly striking. This points to great resistance of the organic matter in the sea bottom to decomposition.

Even more important than the limited decomposition of the organic matter is the fact that the nitrogen is not mineralized at all in the period of time used, namely in 15–30 days. The oxidation process is thus found to take place at the expense of the non-nitrogenous organic complexes in the bottom material. The fact that this organic matter is not uniform in composition, but is made up of a number of organic compounds has been demonstrated previously (*11*).

Of further significance is the fact that the rate of oxidation of the organic matter from bottom deposits nearer to land and from shallower basins is considerably greater than that from bottoms at greater depths and distances. The organic matter in these bottoms is much more resistant, the oxidizability being only one-tenth or one-fifth of that of the organic matter in shallower bottoms near land. This suggests that the organic matter of the latter is more "aged" or has had time to become more highly oxidized.

SUMMARY

1. A study has been made of the rate of oxidation of the organic matter in the sea bottom, as influenced by its abundance, nature of bottom material, distance from land and depth of bottom.

2. A convenient procedure was developed for this study. It consisted in placing definite amounts of fresh bottom material in oxygen bottles containing a known volume of "cultured" water (water kept for several days in the laboratory and resaturated with oxygen). The bottles were incubated for 7–15 days or longer; the clear water was then siphoned into smaller oxygen bottles and the amount of oxygen measured. The results have been calculated on the basis of 1 gm. of dry material. Comparisons were made between the organic matter content, as calculated from the total carbon or nitrogen in the material, and the amount of oxygen consumed.

3. Sandy bottoms were found to consume very little oxygen chemically, while mud bottoms consumed larger amounts. The biological consumption of oxygen by different types of bottom material was considerably greater than chemical absorption.

4. By allowing oxidation of the organic matter to proceed for 15–30 days, it was found that 1 milligram of organic matter in bottoms close to land would consume about 0.1 cc. of oxygen, under the most favorable conditions.

5. The organic matter in sea bottom at greater depths was oxidized to a much lesser extent than the organic matter in shallower bottoms, nearer to land.

6. The organic matter in the sea bottom was found to be much more resistant to biological decomposition or oxidation than had been previously determined for the organic matter in sea water or in the plankton organisms.

7. The oxidation of the organic matter, at least for 15–30 day periods, took place at the expense of the non-nitrogenous constituents; very little of the nitrogen was liberated in a mineralized form in that period of time.

8. It is suggested that the rate of oxidation of the organic matter in the bottom material be used as a measure of the availability or nature of this material.

REFERENCES

1. Allgeier, R. J., Peterson, W. H., Juday, C. and Birge, E. A.
1932. Intern. Rev. Hydrob. *26:* 444–461.
2. Alsterberg, G.
1927. Bot. Notiser (1927): 255–273.
3. Bokova, A., Borsok, V., Verjbinskaia, N., Kreps, E. and Lukyanova, V.
1936. Archiv. Biol. Nauk. *43* (No. 2–3): 353–364.
4. Boysen-Jensen, B.
1914. Rept. Danish Biol. Sta. *22:* 5–39.
5. Brand, T. V., Rakestraw, N. W. and Renn, C. E.
1937. Biol. Bull. *72:* 165–175.
6. Butterfield, C. T.
1929–1931. Publ. Health Repts. *44:* 2865–2872; *26:* 393–426.
7. Kusnetzow, S. I.
1935. Verhandl. Intern. Vereinig. theor. angew. Limnol. *7:* 562–582.
8. Kusnetzow, S. I.
1937. Microbiologia, *6:* 186–201, 465–467.
9. Moore, H. B.
1931. Jour. Mar. Biol. Assn. *17:* 325–358.
10. Moore, H. B. and Neill, R. G.
1930. Jour. Mar. Biol. Assn. *16:* 589–594.
11. Waksman, S. A.
1933. Soil Sci. *36:* 125–147.
12. Waksman, S. A. and Carey, C. L.
1935. Jour. Bact. *29:* 531–543.
13. Waksman, S. A. and Hotchkiss, M.
1937. Jour. Bact. *33:* 389–400.
14. Waksman, S. A., Stokes, J. L. and Butler, M. R.
1937. Jour. Mar. Biol. Assn. *22:* 359–373.
15. ZoBell, C. E. and Anderson, D. Q.
1936. Bull. Amer. Assn. Petrol. Geol. *20:* 258–269.

Contribution No. 166

Reprinted from Ecology, Vol. 19, No. 1, January, 1938
Printed in U. S. A.

SEASONAL CHANGES IN THE INTENSITY OF SUBMARINE ILLUMINATION OFF WOODS HOLE

George L. Clarke

Biological Laboratories, Harvard University, and Woods Hole Oceanographic Institution[1]

Our previous measurements of the penetration of daylight into the sea in the Western North Atlantic were all made during summer months (Clarke, '36a). It therefore seemed extremely desirable to supplement these measurements with observations in other seasons of the year. If the transparency of the water changes materially from month to month, the depth of the "photic zone" and the distribution of radiation within it will be correspondingly altered. A slight change in the value of the transmissive exponent has an appreciable effect after only a few meters of water have been traversed, and at greater depths the difference in illumination rapidly becomes enormous.

Submarine illumination is of prime importance in the production of pelagic plant cells upon which all life in the sea ultimately depends. Any attempt to study the growth of the phytoplankton must take into account not only the seasonal variation in the amount of radiation reaching the earth's surface, but also any seasonal changes in the transparency of the sea water which may occur. As will appear presently, the latter may have a much more profound effect on the illumination at the depths where pelagic plants are living. Similarly, changes in transparency will influence the reactions of photosensitive animals. The extent of the diurnal vertical migration of zooplankton would be altered (cf. Clarke, '34) and the depth at which fish can see would be affected (cf. Clarke, '36b). Accordingly, changes in transparency must have an important bearing on all the ecological relationships within any area from season to season.

During 1935–36 trips were made once or twice a month with the 40 ft. power boat "Asterias" to a station located at the Whistle Buoy at the western entrance to Vineyard Sound where collections of phytoplankton and zooplankton and various hydrographic observations were made to investigate the seasonal production of plankton and the factors influencing it (Clarke and Zinn, '37). For the reasons given above light penetration measurements were made on as many of these trips as possible. I am greatly indebted to Dr. Charles Renn, Mr. Donald Zinn, and Mr. Alfred Woodcock for carrying out the measurements on the occasions when I was unable to go personally. These men and the volunteers who acted as crew are to be credited with successfully carrying out the work each month right through the winter. The choppy sea, which is almost always encountered in this exposed locality, and the ice, which invariably coated the decks and rigging in the cold weather, made the work extremely difficult and precarious. The sea temperature reached a minimum of — 0.8° C. and on one occasion the air temperature was so low that the water beneath the opal glass of the photometer froze before the instrument could be put overboard.

---

[1] Contribution No. 166.

Hydrographic Situation

The Whistle Buoy at the western entrance to Vineyard Sound (Lat. 41° 17′ 35″ N., Long. 71° 0′ 0″ W.) was chosen as the locus of these observations because it was the farthest point toward the open sea which could be visited

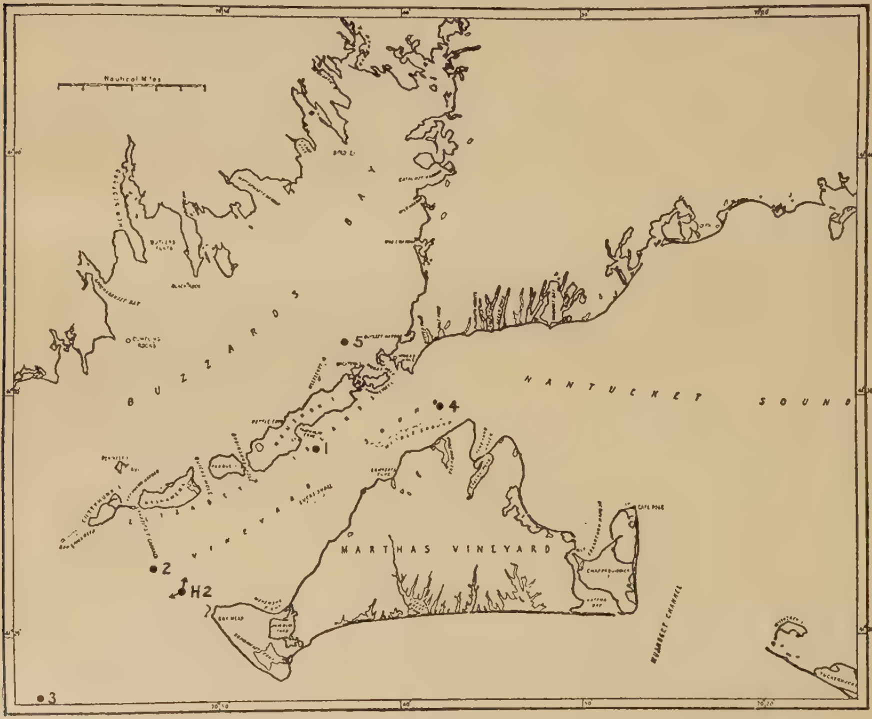


Fig. 1. Map of the Woods Hole region showing the location of Station 3 at the whistle buoy at the western entrance of Vineyard Sound where all the measurements of light penetration reported in this paper were carried out.

from Woods Hole within one day. Cuttyhunk Island lies eight miles to the north, Gay Head on Martha's Vineyard and No Man's Land Island lie eight miles to the east of the Whistle Buoy (marked Station 3 in figure 1). Block Island is twenty-five miles away on the west: To the south the Continental Shelf water extends without obstruction.

The hydrography of the region is complicated because of the notoriously strong tide which runs all along this coast and particularly in Vineyard Sound. At Station H2 (figure 1) of the U. S. Coast and Geodetic Survey the ebb tide was found to flow W.S.W. and the flood tide N.N.E. The ebb tide debouching from Vineyard Sound and Buzzards Bay therefore probably passed largely to the west of the Whistle Buoy where our observations were made. However, since previous measurements had shown that the water in the inner part of the Sound and Bay differs considerably in its optical properties from the water off shore (Clarke and Oster, '34, and Oster and Clarke, '35), it was important to be as sure as possible that no serious contamination from these sources existed at the times when the measurements at the Whistle Buoy were made. To this end the trips were arranged as far as possible on days when the "East," or flood tide, had been flowing for at least an hour, or before the "West" tide had flowed for more than an hour, thus insuring the presence of typical off-shore water. On the few occasions when the observations unavoidably fell on the wrong phase of the tide, the measurements do not show any consistent indication that serious contamination had taken place. It seems safe to assume, therefore, that our station at the Whistle Buoy is far enough off shore to be sufficiently removed from any rapidly fluctuating land influences and to be considered typical of a considerable area.

These tidal oscillations are superimposed upon the much larger but slower coastal current which flows in a southwesterly direction over the Continental Shelf all along this coast. Water is moving continuously from Nantucket Shoals on past New York. It is presuamably from the inner edge of this current that the water at our station is derived. However, there must be a certain admixture of in-shore water, since the salinity value at our station (see fig. 2) was slightly lower at all seasons of the year than that characterizing the water farther off-shore [2] and was slightly higher than that found within Buzzards Bay and Vineyard Sound, according to determinations which we carried out during the summer of 1935. The prevailing wind, which is from the southwest, would tend to blow off-shore water in toward our station. We may suppose, however, that gales from this direction or from other points of the compass disturb the normal hydrographic situation rather profoundly.

INSTRUMENTS

The deck and sea photometers employing Westinghouse Photox Cells described by Powell and Clarke ('36) were used for this investigation. The spectral sensitivity of these cells has a maximum at 5500A and drops off to ten per cent of the maximum at 4650A and 6250A. This "green" component of solar radiation had previously been shown by Oster and Clarke ('35) to penetrate more effectively than the "red" or "blue" components at a station off Gay Head where measurements were carried out on August 17, 1934. The spectral sensitivity of the cells corresponds so closely to that of

---

[2] At Station "Martha's Vineyard I." See H. B. Bigelow and M. Sears, '35.

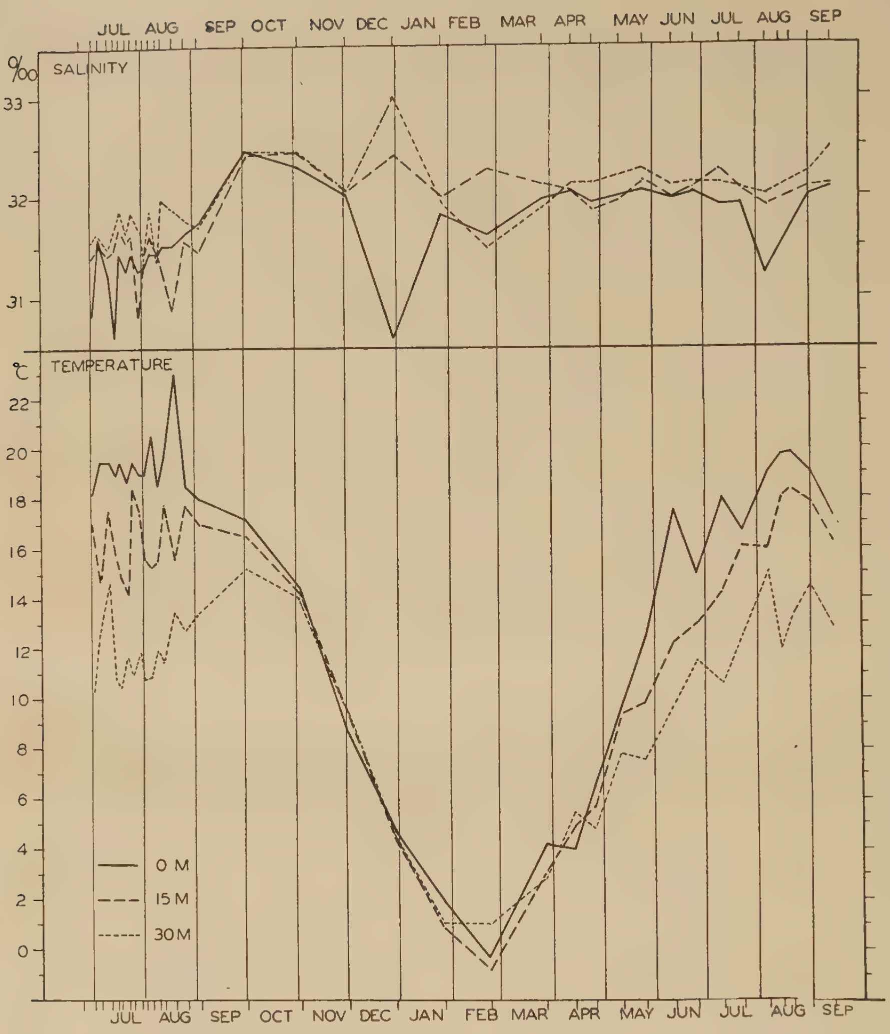


Fig. 2. Variation in salinity and temperature at 0, 15, and 30 m. at the whistle buoy at the western entrance to Vineyard Sound (Station 3) from July, 1935, to September, 1936. The markers on the abscissae indicate the days on which observations were made.

the human eye that we may refer to the light measured as the visible part of the total solar radiation.

The photometers had been standardized against a 1000-watt incandescent lamp and calibration curves relating emission to light intensity had been drawn up in 1935 by Powell and Clarke ('36). These same calibration curves were used for the calculation of light intensity in the present investigation. When the photometers were restandardized in September, 1936, their emissions to the same intensity were found to have dropped about 25 per cent (cf. Poole and Atkins, '33 and '35). This reduction in emission introduces no error as far as the transparency measurements are concerned because the sea photometer and the deck photometer are always compared before and after each series of observations, and the light intensity at each depth is found as a percentage of that measured by the deck photometer. However, a recalibration of the instruments against the photoelectric cell in December, 1936, showed that the shape of the curves relating emission to light intensity had changed. Since the amount of the shift varied widely in different parts of the range, and since the time when the change occurred is not known, it is impossible to assign a value to the error introduced. But five of the series of observations were recalculated on the basis of the 1936 calibration and the values thus obtained for the transmissive exponent have been added to figure 5 and placed in parentheses in table I. Of these the greatest discrepancy is in Series 431 where a change of 25 per cent is brought about. Although the occurrence of this error is unfortunate, its magnitude is small compared to the changes observed in the transparency of the water, and hence should not affect our general conclusions. The photometers will be retested from time to time in the future to detect any further change and

TABLE I. *Summary of observations during 1935–36 at Whistle Buoy at western entrance to Vineyard Sound (Station 3)*

Series No.	Date	Time L.A.T.	Av. transmissive exponent, k,[1] over range in next col.	Range (Meters)	Time and direction tide had flowed (Hours)
416[2]	Nov. 2, 1935	11:26	.26	1–17	E. 5¾
417	Dec. 1	12:26	.36	1–13	E. 3¼
418	Dec. 29	14:06	.14 (.16)[3]	1–30	W. ¼
419	Jan. 27, 1936	13:46	.30 (.33)	1–19	E. 6
420	Feb. 23	14:16	.13	1–31	W. 2½
421	Mar. 27	14:06	.19	2–19	E. 5½
422	Apr. 13	10:36	.12	1–25	E. ½
423	Apr. 25	10:56	.13	1–27	E. 2½
424	May 11	10:46	.090	8–28	E. 2
425	May 25	13:31	.12	2–28	E. 4¾
426	June 11	13:46	.14	1–27	E. 4
427	June 25	13:16	.16	1–28	
			.23	2– 8	E. 4
428	July 10	14:31	.12	12–31	E. 5
429	July 22	14:14	.14	1–28	W. ¼
430	Aug. 6	13:16	.13	1–20	E. 5¾
431	Aug. 20	14:18	.14 (.18)	1–29	W. ¾
432	Aug. 31	13:31	.15 (.18)	10–30	W. 3¼
			(.13)	10–26	
			(.37)	26–30	
433	Sept. 13	14:06	.16 (.18)	9–30	W. 4½
434	Dec. 27	15:01	(.24)	1–24	W. 5¼

[1] In the equation $I/I_0 = e^{-kL}$ where L is the thickness of the water layer (in meters) in which the intensity is reduced from I_0 to I.

[2] This observation was made in Vineyard Sound at a point midway between Gay Head and Cuttyhunk (Station 2).

[3] Values in parentheses based on the 1936 calibration.

it is suggested that investigators using other types of rectifier cells report on the constancy of their cells in this respect in order that their suitability for this type of work may be judged.

Measurements were ordinarily made at depths of 1, 2, 3, 4, 6, 8, 10 meters and thence every 3 m. to the bottom, which varied in depth from 27 m. to 32 m. When possible, readings were also taken at 0.5 m. to continue the study of the surface effect (Powell and Clarke, '36). In all measurements the same procedure was followed and the same precautions taken as have been described in our previous publications.

Changes in Transparency

The eighteen series of measurements which were carried out between November 2, 1935, and September 13, 1936, have been summarized in table I. An additional series of measurements was made on December 27, 1936, after the Photox Cells had been recalibrated and remounted in the photometer cases.[3] Eight respresentative series have been plotted in their entirety (figs. 3 and 4). In figure 3 are shown the curves with the greatest and the least transmissive exponents and two with intermediate values. The curves in figure 4 are those which show the greatest departure from straight lines. It is seen that on most occasions the transparency of the water is very nearly constant throughout the water column and we may therefore use the average value of the transmissive exponent in comparing one curve with another.

During the winter months the temperature curves (fig. 2) indicate that the water is thoroughly stirred from top to bottom and a uniform transparency is to be expected. But with the distinct temperature stratification which appears in summer, it is perhaps surprising that in the majority of cases the rate of transmission should be so constant. However, in Series 432 (August 31) the value of the transmissive exponent from 26 to 30 meters is almost three times as great as that from 10 to 26 meters. We have no information as to the possible cause of the change in transparency in this case. Series 427 (June 25) gives indication of a stratum of reduced transparency existing between two and eight meters. On this occasion total phytoplankton counts and detritus estimations were made as follows (Lillick, '37):

2 m.	26 cells/cc.	Mostly flagellates and peridineans	Detritus: 2[4]
15 m.	2	Mostly flagellates	1
30 m.	6	" "	3

---

[3] The same Westinghouse microameter was used but a new shunt of more rugged and moisture-proof construction, built by the General Radio Co., was installed in place of the old one.

[4] From microscopic examination of the centrifuged material from water samples. The samples were graded from one to five, those given a value of one having the least amount of detritus.

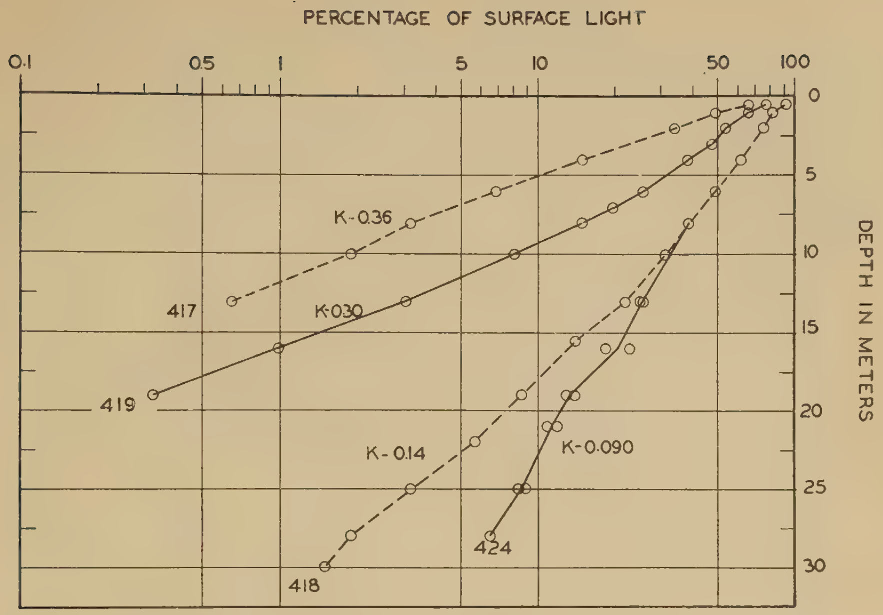


FIG. 3. Relation between depth and irradiation expressed as a percentage of the light just over the surface (logarithmic scale). Observations made at the whistle buoy at the western entrance to Vineyard Sound. Series number indicated at end of each curve. For data see table I.

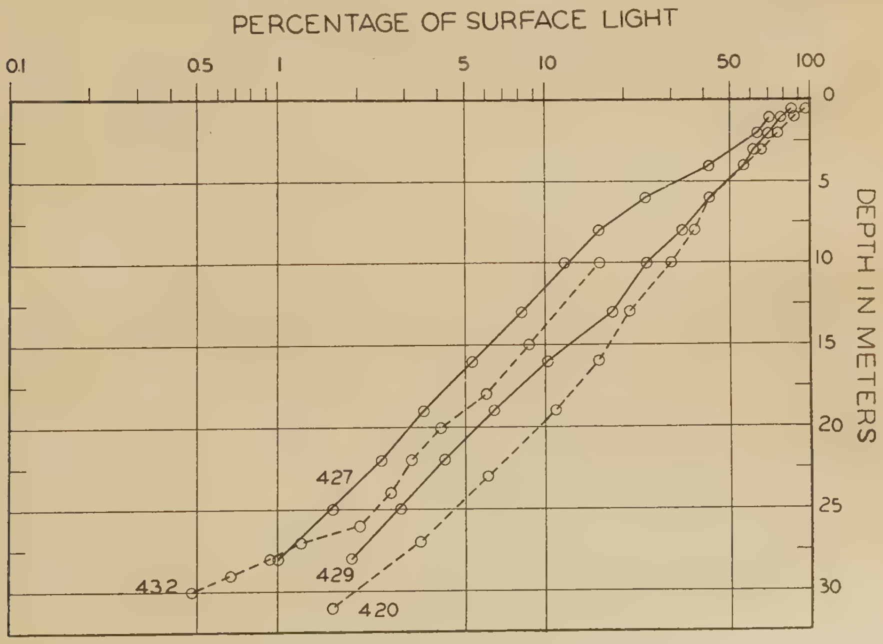


FIG. 4. Relation between depth and irradiation expressed as a percentage of the light just over the surface (logarithmic scale). Observations made at the whistle buoy at the western entrance to Vineyard Sound. Series number indicated at end of each curve. For data see table I.

Thus in this case the diminished transparency of the upper strata coincides with a concentration of microorganisms, but on several other occasions on which equally great irregularities in the vertical distribution of phytoplankton and of detritus occurred the transparency was found to be uniform from top to bottom. Similar situations have been reported before (Clarke, '33a; and Clarke and Oster, '34). This whole question of the causes of changes in transparency will be considered below in greater detail.

In those cases in which a reliable measurement could be obtained at 0.5 m. it is found that, when plotted, a break in the curve appears at 1 m. The reduced slope of the curve from 1 m. to the surface indicates the presence of a stratum of relatively opaque water just beneath the surface. These cases confirm the findings of Powell and Clarke ('36) and account for a large part of the so-called "surface loss."

The values of the average transmissive exponents throughout the year (table I and fig. 5) range from a minimum of $k = .090$ on May 11 (Series 424) to a maximum of $k = .36$ on December 1 (Series 417). Thus the water was four times more transparent on May 11 than on December 1. Transparency was low on November 2, 1935, December 1, 1935, and January 27, 1936, but water of relatively high transparency occurred on December 29, 1935. However the additional series of measurements made a year later on December 27, 1936 (Series 434) revealed a low transparency. This indicates that the high transparency observed on the previous occasion for the end of December may have been exceptional. These differences in transparency are far beyond any instrumental or observational error. Rather great fluctuations continued during the early months of 1936 until April, after which more uniform values were obtained. All four measurements in April and May indicated high transparencies, and relatively clear water continued during the summer months, contrary to the prevalent idea that at this season the water becomes cloudy with planktonic organisms.

The curve representing the seasonal changes in transparency may be compared with the curves showing the contemporaneous variations in the abundance of zooplankton, phytoplankton, and detritus(fig. 5) in an attempt to find the primary cause of these changes. On December 1 the opacity of the water was very much greater than on November 2, but the abundance of phytoplankton had dropped from a high maximum to a low value and there had been slight reductions in the amounts of zooplankton and detritus. On December 29 the water was found to be very transparent, but there was no change in the abundance of zooplankton nor of phytoplankton and a slight increase in detritus had occurred. The high value of the transmissive exponent on January 27 coincides with peaks in the phytoplankton and detritus curves, but the high value of the exponent on March 27 corresponds to low points on these curves. During the summer months considerable fluctuations in the zooplankton and in the detritus took place but the transparency remained quite constant.

In this series of observations we therefore have only one clear-cut case (January 27) of an abundance of plankton corresponding with a decrease in transparency and there are so many cases of negative correlation that we are forced to conclude that for the year as a whole changes in the plankton have little to do with the transparency. The estimations of the detritus were admittedly very rough and cannot be relied upon too heavily. A more careful investigation of the nature and abundance of detritus should be undertaken to ascertain exactly its influence on transparency under various circumstances (cf. Pettersson, '35).

The profound fluctuations in transparency observed during the winter months might be explained on the basis of a movement of offshore water into our station on certain occasions if the optical properties of the new bodies of water were different. Periods of relative opacity might be caused by winter storms violent enough to stir up sediment from the bottom. If this explanation were valid, we should expect to have found corresponding peaks in the detritus curve. What factors cause changes in transparency, if plankton and detritus do not, is a matter which needs investigation. Although we did not know in what way the wind might exert its effect, we nevertheless investigated the force and direction of the wind during the periods of the winter observations to ascertain whether any correspondence existed with the changes in transparency (table II). The force of the wind, as indicated by its total movement, was great and approximately equal during the periods ending December 29 and January 27 and was less and approximately equal on the other occasions. This is in utter disagreement with the changes in transparency. Similarly changes in the direction of the wind exhibit no correspondence with the transparency. The periods ending December 29 and January 27 are particularly striking in the similarity of their meteorology, but the water nevertheless differed profoundly in its transparency.

The seasonal variation in transparency at our station is of about the same magnitude as that observed by Poole and Atkins ('29) throughout the year 1928 in the English Channel and also as that observed by Williams and Utterback ('35) near Puget Sound. Poole and Atkins reported that there were no regular seasonal changes in the opacity of the water. The main spring diatom outburst in 1928 failed to produce any very noticeable obscuring effect. Increase in transparency seemed to be due, on certain occasions at least, to an influx of clearer water from further off-shore. There was some evidence that changes in the transparency at different levels was due to alterations in the depth at which zooplankton aggregated. Williams and Utterback found that a decrease in transparency occurred during the spring at their stations, the opacity reaching a maximum for the year in May or June. These investigators assert that " the observed seasonal variations in the coefficients are caused by changes in the amount and kind of suspended matter. While at present it is not possible to decide whether the variations are caused by the total plankton in the water, the data presented show considerable

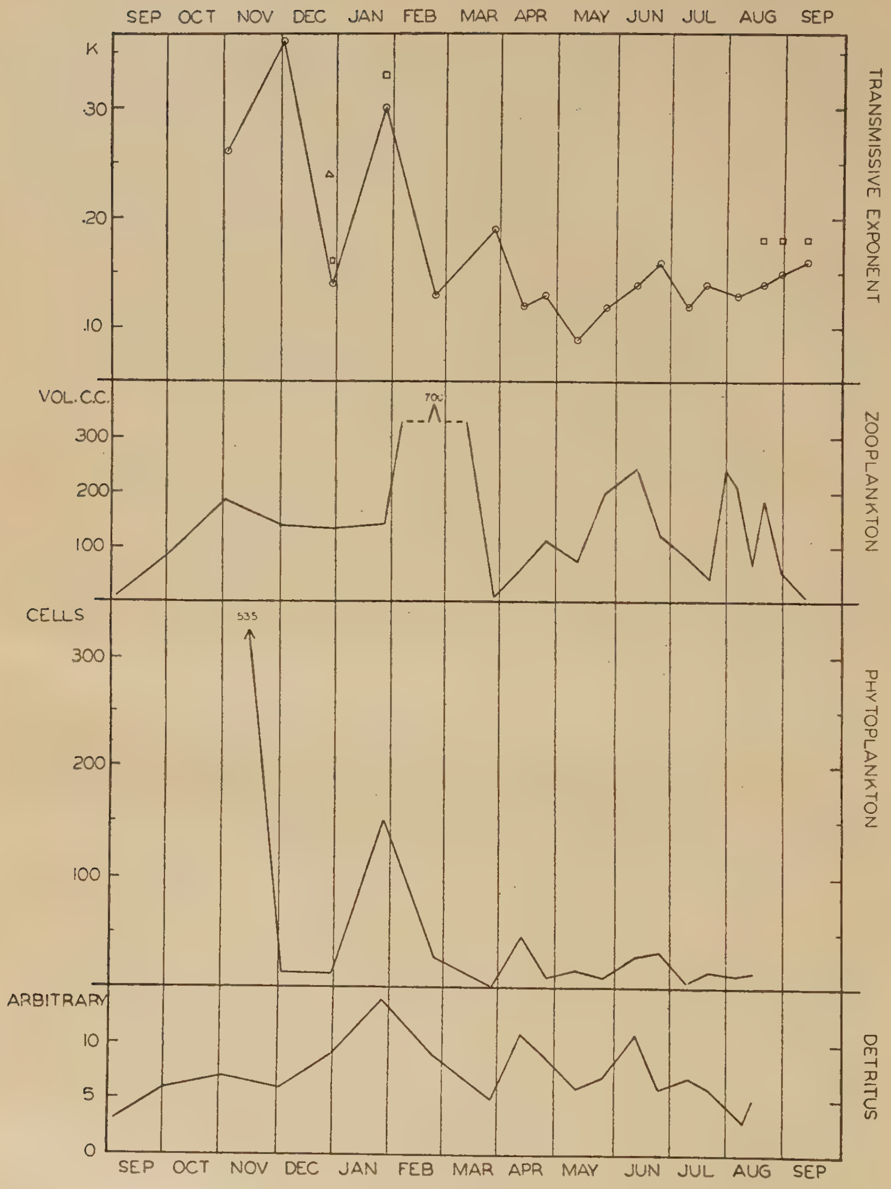


FIG. 5. Seasonal changes in the average value of the transmissive exponent, *k*, and in the amounts of plankton and detritus at Station 3 during 1935–36.

Transmissive exponent—circles mark values based on 1935 calibration; squares mark values based on 1936 calibration; triangle marks an observation made a year later, on December 27, 1936.

Zooplankton—total zooplankton taken in 30 min. oblique hauls with 75 cm. scrim net. Approximate volumes after settling one month. Hauls consisted mostly of copepods except those on December 29, January 27, and February 23, which were mostly sagittae.

correlation." It may be that the causes of changes in transparency are not the same in different parts of the ocean, but since we have such widely divergent opinions on this matter and so much apparently conflicting evidence, it is obvious that the whole question should be made the subject of a thoroughgoing investigation.

Discussion

Our measurements indicate that during the spring and summer months the transparency of the water at our point of observation remains relatively constant and that there are no such profound fluctuations as were observed in the winter months. Evidently the transparency is generally low during the winter because of the six observations which were made from November through February, four show the presence of water which is very much more turbid than was ever found in the summer. One is curious to know, however, to what extent the high transparencies found on December 29 and February 23 are exceptional and how long such conditions of high transparency will ordinarily last. The answer to this question must await further investigation with more closely spaced observations. Another problem is to what distance off shore the effect of detritus stirred up during storms is felt,—if indeed detritus is found to influence transparency. Further measurements are needed here also, but the inference is that in deeper water—and certainly after the edge of the Continental Shelf is passed—great changes in transparency from this cause would not be encountered.

To determine exactly how great an effect the observed changes in the transparency at our station would have on the illumination reaching different depths, a series of calculations has been made which take into account not only the change in the clearness of the water, but also the variation in the amount of light reaching the earth's surface from month to month. Since green plants are capable of utilizing light over a wide range of intensities, and since the length of day differs so greatly with the season in our latitude, the significant aspect of the illumination from the point of view of the phytoplank-

---

The net used catches effectively animals as large as, or larger than, copepodid Stage IV of *Calanus finmarchicus*. Many smaller forms are not retained by the net (from Clarke and Zinn, '37).

Phytoplankton—total number of phytoplankton cells in 3 cc.; values plotted are the sums of the numbers of diatoms and flagellates per cc. found in water samples from 2, 15, and 30 m. The dominant forms on November 2 and January 27 were respectively *Nitzschia seriata* and a small peridinean. The larger diatoms were relatively scarce at all times. The most abundant occurrence of a large species was on April 13 when *Guinardia flaccida* was found in a concentration of eighteen cells per cc. (from Lillick, '37).

Detritus—rough estimation from microscopic examination of the centrifuged material from water samples. The samples were graded from one to five, those given a value of one having the least amount of detritus. The values plotted are the sum of the values at each of the three depths (Kindness of Miss Lois Lillick).

TABLE II. *Movement of wind at Block Island on the days of the first six light intensity measurements and on the six preceding days in each case*

Date		Total movement (miles)	Prevailing direction
Oct.	27	254	S.W.
1935	28	239	S.W.
	29	303	S.E.
	30	386	E.
	31	602	N.E.
Nov.	1	553	N.E.
	2	308	N.E.
		Total 2645	
Nov.	25	476	N.W.
	26	441	N.W.
	27	226	S.
	28	536	S.
	29	489	W.
	30	342	W.
Dec.	1	197	N.W.
		Total 2707	
Dec.	23	346	N.
	24	531	N.W.
	25	460	N.W.
	26	612	N.
	27	806	N.W.
	28	678	N.W.
	29	434	N.W.
		Total 3867	
Jan.	21	366	W.
1936	22	334	S.
	23	878	W.
	24	840	W.
	25	682	W.
	26	422	N.W.
	27	455	N.W.
		Total 3977	
Feb.	17	248	N.E.
	18	598	N.W.
	19	500	W.
	20	134	E.
	21	239	N.E.
	22	498	N.
	23	459	N.W.
		Total 2676	
Mar.	21	312	S.
	22	661	W.
	23	500	W.
	24	190	S.E.
	25	279	E.
	26	219	S.W.
	27	355	S.E.
		Total 2516	

ton is the total amount of radiation available per day. In the case of the animals, on the contrary, in so far as we are interested in their vision or their phototropic movements, it is the intensity of the light at any given moment with which we are primarily concerned. Since the animals are not necessarily active all day, the most significant value of the intensity to use for the comparison of one season with another is the maximum intensity reached each day.

The nearest point to our station at which a continuous record of daylight was kept is the Blue Hill Observatory, 70 miles to the north. I am indebted to Dr. C. F. Brooks, in charge of the Observatory, and his staff for their kindness in supplying me with the data which appears below. At Blue Hill the total solar radiation (direct plus diffuse) falling on one square centimeter of horizontal surface is measured by means of an Eppley pyrheliometer. The average value for each week of the total daily radiation for the twelve-month period of our observations has been plotted in figure 6. The graph shows that even these weekly average values fluctuate widely. The minimum average value was 50 gram cal./cm.^{2} per day for the week of November 12, 1935, and the maximum was 702 gram cal. for the week of May 20, 1936. The lowest total for a single day was 19.2 gram cal. on November 16, 1935, and the highest was 814.4 on July 1, 1936. Therefore the amount of radiation on the brightest day was over 40 times that received on the darkest day within this period. On the average, however, the amount of radiation reaching the earth's surface per day in this region in the summer is only about four times as great as in the winter. A similar conclusion may be drawn from the curve based on the calculations of H. H. Kimball ('28) for the radiation which is received at the surface of the ocean east of Cape Cod (Lat. 42° N. Long. 66–70° W.) under conditions of average cloudiness. At Plymouth, England (Lat. 50° N.), Atkins and Poole ('36) found that the maximum value of the "daily vertical illumination integral" as measured by a sodium photoelectric cell was 64 times the minimum value. The ratio of the mean daily value for the darkest month to that for the brightest month was 1 : 12.8. This greater seasonal variation is to be expected from the difference in latitude.

The changes during the year in intensity rather than in total amount of light may be appreciated by reference to the curve in figure 6 representing the maximum value each week for the radiation received during one hour at Blue Hill. The lowest maximum hourly value was 18.9 gram. cal. in the week of November 12, and the highest value was 104.4 gram cal. in the week of June 24. The difference in the maximum intensity reached on a dark day and on a bright day within the same week is often very great. For instance, on June 20, 1936, the maximum hourly radiation was 21.8 gram. cal. in contrast to the high value of 104.4 attained four days later. On the darkest single day of the year, November 17, 1935, the maximum hourly radiation was 3.5 gram cal., but a few days later a value of 49.7 was observed. The maximum hourly radiation on the brightest day of the year was thus thirty times the maximum

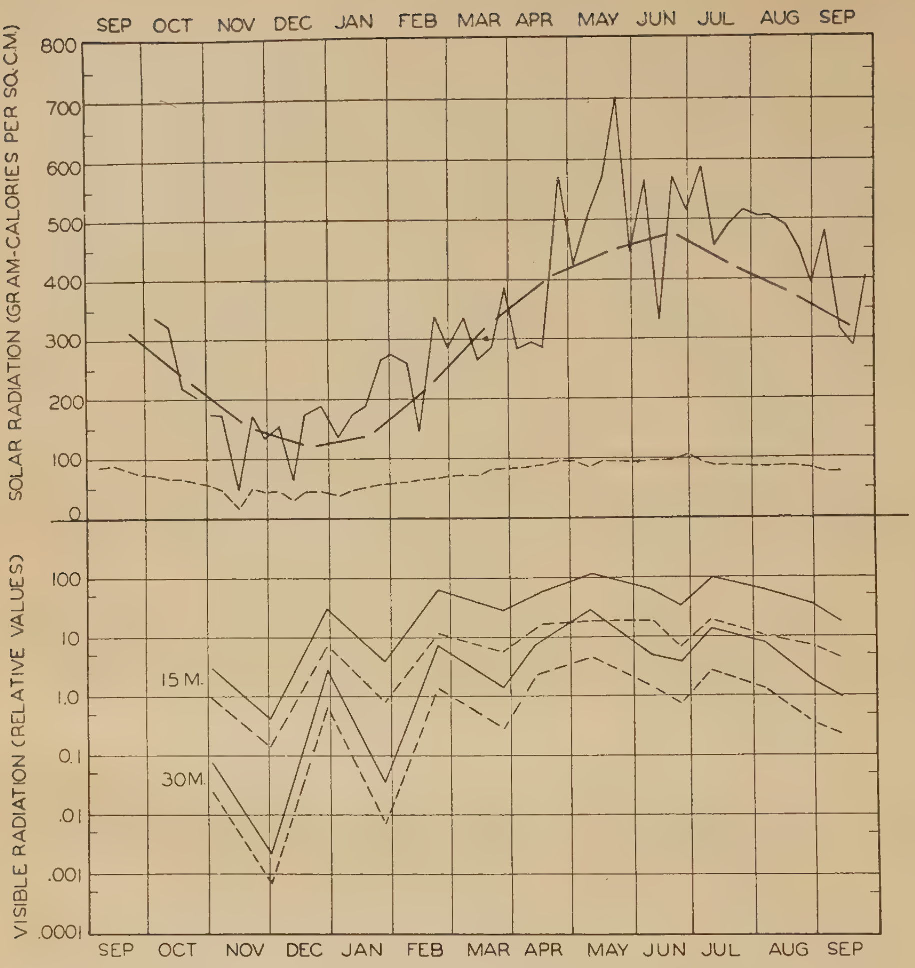


Fig. 6. Upper Section: Solid line—average for each week of the total solar radiation (direct + diffuse) per day received on a horizontal surface at Blue Hill for 1935–36 (October values from 1934).

Heavy broken line—calculated average value for the 21st of each month for total solar radiation (direct + diffuse) per day with average cloudiness received on a horizontal surface at the surface of the ocean at a position 42° N. latitude and 66–70° W. longitude (from H. H. Kimball, '28).

Light broken line—maximum value in each week of the radiation received per hour at Blue Hill for 1935–36 (total solar radiation, direct + diffuse, received on a horizontal surface).

Lower Section: (Logarithmic Scale). Visible radiation at depths of 15 m. and of 30 m. at the whistle buoy at the western entrance to Vineyard Sound during 1935–36.

Solid lines—total visible radiation per day. Values obtained by multiplying the percentage of the surface illumination reaching each depth by the average total solar radiation per day received at Blue Hill during the same week (solid line in Upper Section).

Broken lines—maximum value of visible radiation received per hour. Values obtained by multiplying the percentage of the surface illumination reaching each depth by the maximum value of the solar radiation received per hour at Blue Hill during the same week (light broken line in Upper Section).

hourly radiation on the darkest day, but one sees from the curve that on the average the maximum hourly radiation during the summer is only about twice as great as that found during the winter. Atkins and Poole ('36) report a similar difference in intensities reached on the brightest and on the darkest days of the year, but the average value for July at Plymouth is over eight times as great as the average for December.

The depths of 15 m. and of 30 m. (which is roughly equivalent to the bottom) were chosen for calculations of the seasonal variation of the light beneath the surface. From the penetration curves the percentages of surface light reaching these depths each month were found. These percentages were then applied to the Blue Hill values for average total daily radiation and for maximum hourly radiation within the same week, and the results plotted in the lower section of figure 6. The numerical values obtained are only relative, however, because the percentages used were based on the penetration of the visible part of the spectrum whereas the Blue Hill values represent total solar radiation. A suitable factor could be applied to our results to convert them into absolute units if we knew the proportion of the total solar radiation which fell within the visible. Atkins ('32) states " The division is approximately ultraviolet 12 per cent, visible 37 per cent, and infra-red 51 per cent." But unfortunately this relationship varies according to the altitude of the sun and to the amount of moisture, dust, etc. in the atmosphere. Changes in the shape of the solar envelop are presented graphically by Atkins. Furthermore, any attempt to convert our values into absolute units would have to take into consideration the curve of sensitivity within the visible region for the submarine photometer used. For these reasons and the fact that animals and plants differ in their sensitivity to different regions of the visible spectrum, it was thought best to leave the results as relative values. The only error now included is that due to differences in the distribution of energy within the solar spectrum at different seasons. Such an error is obviously infinitesimal compared to the tremendous changes observed in the submarine illumination.[5]

The curves representing the illumination at 15 m., which have been plotted on a logarithmic scale, show that the greatest value of the total daily illumination in May was about 300 times the smallest value in December. The value of the maximum hourly illumination varied over a range of one to 100. Since changes in the transparency of the water have a cumulative effect as more and more meters are traversed, the variation in the illumination received by an organism living on the bottom at 30 m. will obviously be much greater than that experienced at 15 m. Thus it is seen from the curves that the greatest value for the total daily illumination at 30 m. was over 10,000 times the least. Similarly, the greatest value for the maximum hourly illumination at 30 m. was about 7000 times the least.

[5] Atkins and Poole ('36) found a surprisingly close agreement between their records for the fluctuations in violet light at Plymouth and the records for the total spectrum at London.

The importance of changes of this magnitude for the fauna and flora needs no comment. Let it be pointed out, however, that these tremendous differences are due largely to fluctuations in the transparency of the water, for as we have seen, the seasonal change in illumination at the surface is of a lower order. From figure 5 we see that the transparency of the water on December 29 was the same as on June 11. The light reaching 30 m. on the latter date amounted to about twice as much as on the former. This is the effect of the seasonal change in daylight alone. Conversely, at the beginning and at the end of December the light reaching the earth's surface was about the same, but the difference in the transparency of the water caused a 100-fold change in the illumination at 15 m. and a 1000-fold change at 30 m. Another example may be found in comparing June 25 with July 10. On these days the radiation at the surface was nearly the same, but the slight increase in transparency on the latter date resulted in a well-marked increase in the submarine illumination.

The foregoing observations and calculations have provided a general picture of the approximate magnitude of the changes in submarine illumination which are to be expected from day to day and from month to month due to the varying amounts of daylight reaching the earth's surface and to the changes in transparency. Of these two factors this investigation has shown that the latter may be of much greater importance than the former for coastal waters at depths of more than only a few meters. We may conclude, therefore, that in investigating the photosynthesis of the phytoplankton during the course of a season, or in analyzing the reactions of animals to light at different times, the greatest care must be taken to measure the rate of light penetration and to make due allowance for even the smaller changes in transparency that may occur.

Summary

1. The penetration of light into the sea at a station at the western entrance of Vineyard Sound was measured at monthly intervals during 1935–36 using the Photox photometers previously described (maximum sensitivity in the green).

2. The hydrography of the region is complicated by the existence of strong tides but evidence is given for believing that the station is typical of a considerable area.

3. The transparency of the water was generally uniform from top to bottom. Irregularities in the vertical distribution of plankton and detritus were not as a rule reflected in the relative transmission at different depths.

4. The transparency was variable but usually low during the winter months and relatively uniform and high in the summer. The value of the average transmissive exponent ranged from $k = .090$ (on May 11) to $k = .36$ (on December 1).

5. The seasonal changes in transparency were carefully compared with the contemporaneous variations in the abundance of zooplankton, phytoplankton, and detritus and in the force and direction of the wind, but no sustained correlation was found. Comparison with other investigations is made on this point.

6. Data obtained from the Blue Hill Observatory show that the amount of radiation reaching the earth's surface in this region per day is on the average about four times as great in summer as it is in winter. The maximum hourly radiation during the summer is in general only about twice as great as that found during the winter.

7. The fluctuations in the illumination received at two depths during the year due to the combined effect of the seasonal changes in transparency and in amount of radiation reaching the earth have been calculated and found to be very large. The greatest value for the total daily illumination at 30 m. was over 10,000 times the least. Changes in transparency are responsible for the major part of these fluctuations and should be seriously taken into account in investigations in which submarine illumination plays a part.

Literature Cited

Atkins, W. R. G. 1932. Solar radiation and its transmission through air and water. *Journ. Conseil* **7** (2): 171–211.

Atkins, W. R. G. and H. H. Poole. 1936. The photo-electric measurement of the diurnal and seasonal variations in daylight and a globe integrating photometer. *Phil. Trans. Roy. Soc. London, Ser. A* **235**: 245–272.

Bigelow, H. B. and M. Sears. 1935. Studies of the waters on the continental shelf, Cape Cod to Chesapeake Bay. II. Salinity. *Papers in Physical Oceanography and Meteorology* **4** (1): 1.

Clarke, G. L. 1933a. Observations on the penetration of daylight into mid-Atlantic and coastal waters. *Biol. Bull.* **65** (2): 317–337.

——. 1933b. Diurnal migration of plankton in the Gulf of Maine and its correlation with changes in submarine irradiation. *Biol. Bull.* **65** (3): 402.

——. 1934. Further observations on the diurnal migration of copepods in the Gulf of Maine. *Biol. Bull.* **67**: 432.

——. 1936a. Light penetration in the western north Atlantic and its application to biological problems. *Rapports et Procès-Verbaux. Con. Perm. Intern. Exp. Mer.* **101** (Pt. 2): 3–14.

——. 1936b. On the depth at which fish can see. *Ecology* **17**: 452–456.

Clarke, G. L. and R. H. Oster. 1934. The penetration of the blue and red components of daylight into Atlantic coastal waters and its relation to phytoplankton metabolism. *Biol. Bull.* **67**: 59–75.

Clarke, G. L. and D. J. Zinn. 1937. Seasonal production of zooplankton off Woods Hole with special reference to *Calanus finmarchicus*. *Biol. Bull.* **73**: 464–487.

Kimball, H. H. 1928. Amount of solar radiation that reaches the surface of the earth on the land and on the sea, and methods by which it is measured. *Monthly Weather Review* **56**: 393–399.

Lillick, L. C. 1937. Seasonal studies of the phytoplankton off Woods Hole, Massachusetts. *Biol. Bull.* **73**: 488–503.

Oster, R. H. and G. L. Clarke. 1935. The penetration of the red, green, and violet components of daylight into Atlantic waters. *J. Opt. Soc. Am.* **25**: 84–91.

Pettersson, H. 1935. Submarine daylight and the transparency of sea water. *J. du Conseil Perm. Int. pour. l'Exp. de la Mer* **10**: 48–65.

Poole, H. H. and W. R. G. Atkins. 1929. Photo-electric measurements of submarine illumination throughout the year. *Journ. Mar. Biol. Ass. n.s.* **16**: 297–324.

——. 1933. Some experiments on the suitability of rectifier photo cells for the measurement of daylight. *Sci. Proc. Roy. Dublin Soc.* **20**: 537–546.

——. 1935. The standardization of photo-electric cells for the measurement of visible light. *Phil. Trans. Roy. Soc. London.* Ser. A, no. 745, **235**: 1.

Powell, W. M. and G. L. Clarke. 1936. The reflection and absorption of daylight at the surface of the ocean. *J. Opt. Soc. Am.* **26**: 111–120.

Williams, E. A. and C. L. Utterback. 1935. Seasonal changes in components of submarine daylight. *J. Opt. Soc. Am.* **25**: 384.

Contribution No. 167

A BATHYTHERMOGRAPH

By

ATHELSTAN F. SPILHAUS

*New York University**

In the study of the homogeneous layer in the ocean, Rossby[1] found it desirable to have an instrument which would provide a continuous record of temperature against pressure in the surface layers of the ocean. A preliminary instrument named an "oceanograph" was constructed and used during the summer of 1934. The manifold uses to which such an instrument could be put presaged a widespread employment of the apparatus. This, however, did not come about because of certain inherent difficulties in Rossby's design. The record was made on a large smoked foil, and thus entailed the attachment of multiplying linkages to the actuating elements for pressure and temperature. Such multiplying linkages are uncertain in action in sea water, and, furthermore, the size of the instrument to accommodate them must necessarily be fairly great. At Prof. Rossby's suggestion, the author attempted to modify the oceanograph so that it would be more suitable for routine use. The modifications were made with the following aims in view:

(*a*) The instrument should if possible be small enough so that it can be lowered on an ordinary log line by hand if necessary, thus enabling it to be utilized on vessels not equipped with a hydrographic winch.
(*b*) The instrument should be sufficiently rapid in its response such that regardless of the rate at which it passes through the water no errors due to the lag of the thermometric element will be apparent.
(*c*) Care should be taken to eliminate hysteresis of the pressure element.
(*d*) The plates on which the record traces are made should be easily inserted and removed and easily evaluated.

DESCRIPTION OF THE INSTRUMENT

The instrument finally evolved consists essentially of a pressure element comprising an hermetically sealed sylphon inside of which is a guide and compression spring to give the requisite pressure range. Mounted on the movable end of the pressure element is a straight bi-metal strip, and thus

---

*Joint contribution from Woods Hole Oceanographic Institution (No. 167) and New York University.

[1] C.-G. Rossby and R. B. Montgomery. "The Layer of Frictional Influence in Wing and Ocean Currents." Papers in Phys. Oceanography and Meteorology of the Mass. Inst. of Tech. & Woods Hole Oceanographic Inst., Vol. III, No. 3, p. 73.

Reprint from SEARS FOUND. JOURN. MAR. RES.

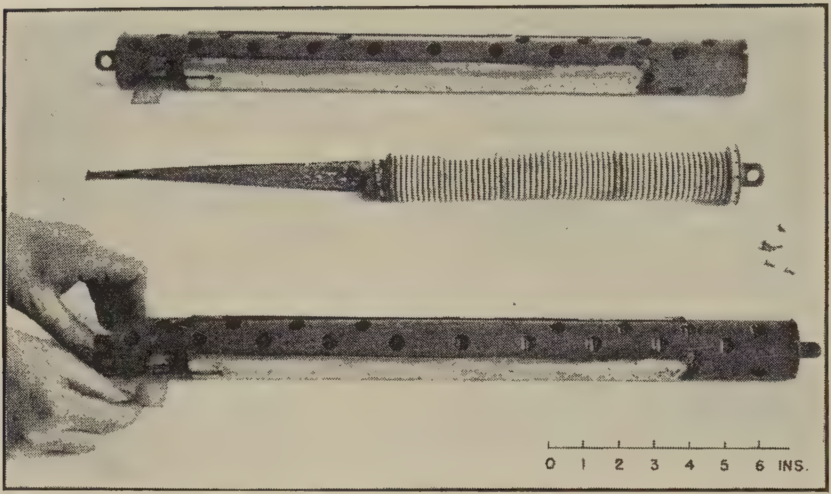


Figure 30. The bathythermograph.

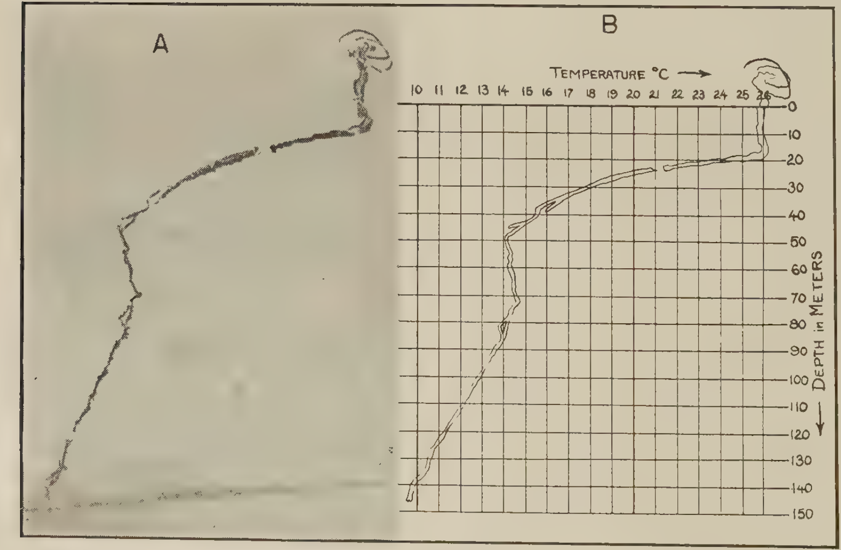


Figure 31. Photographic enlargement (A) from an original record of the bathythermograph, with key diagram (B) showing trace superimposed upon calibration chart.

motion with pressure is at right angles to the deflection of the strip with temperature. At the end of the bi-metal strip a fine needle point is arranged to inscribe a trace on a small glass slide. The slide is prepared for the record by coating it with a thin layer of oil and then smoking the glass to slightly blacken it. The function of the oil is to prevent the smoked film being washed off by the sea water. In view of the fact that the motion of the inscribing point is in two dimensions, the plate which receives the record is held perfectly rigidly in the body of the instrument, and thus insertion and extraction of the plates are entirely independent of the sensitive actuating elements. Figure 30 shows the complete instrument in the lower photograph and indicates the method of insertion of the glass slide to take the trace, while the upper part of the illustration gives a view of the instrument partly disassembled to show the simplicity of the actuating elements. Figure 31 is a photographic enlargement of an original record from the small slide, and the accompanying key diagram shows the trace superimposed on a calibration grid. It can be seen that the record consists of two lines—one made during the descent of the instrument, and the other during the ascent. It can be easily shown that hysteresis of the pressure element and lag of the temperature element both act in such a way as to separate the ascent and descent traces; so that if either pressure hysteresis or thermal lag are present to a marked degree, two distinct traces would have been recorded. The coincidence of the two curves, however, insures that the instrument is functioning correctly. From the standpoint of thermal lag the record is particularly remarkable when it is realized that in the case of the particular test in the photograph the instrument was sent down and brought up through the water at a rate of 100 meters per minute. Thus the whole test down to a depth of 150 meters was completed in 3 minutes. Evaluation of the record obtained is simply accomplished by projecting it by means of a miniature camera projector on to a calibrated screen. Tests were made by lowering the bathythermograph on the end of a log line and it was found that good records could be obtained by an ordinary seaman.

SOME RESULTS OF MEASUREMENTS MADE WITH THE BATHYTHERMOGRAPH

On a cruise made by the "Atlantis," research ship of the Woods Hole Oceanographic Institution, measurements with the bathythermograph were carried out almost hourly for a period of two days, and remarkably sudden discontinuities in the thermocline and inversions of the thermocline were revealed. Figure 32 is a plot showing the temperature variation with depth on the horizontal and vertical axes respectively, while the time changes are set off along the oblique third axis. The bathythermograph records were traced directly on to this diagram from photographic enlargements of the original traces. This figure served to illustrate several points.

(*a*) Abrupt changes in the thermocline are shown, and it should be stressed that these changes must be actually present because they are in every case substantiated by the coincidence of the up and down trace of the bathythermograph.

(*b*) The temperature depth structure below 50 meters is quite complicated, especially for those tests between 1900 and midnight. Thus it is evident that if water bottles were used these intricacies of the temperature curve would be entirely overlooked, owing to the necessarily wide spacing of the bottles below 50 meters.[2]

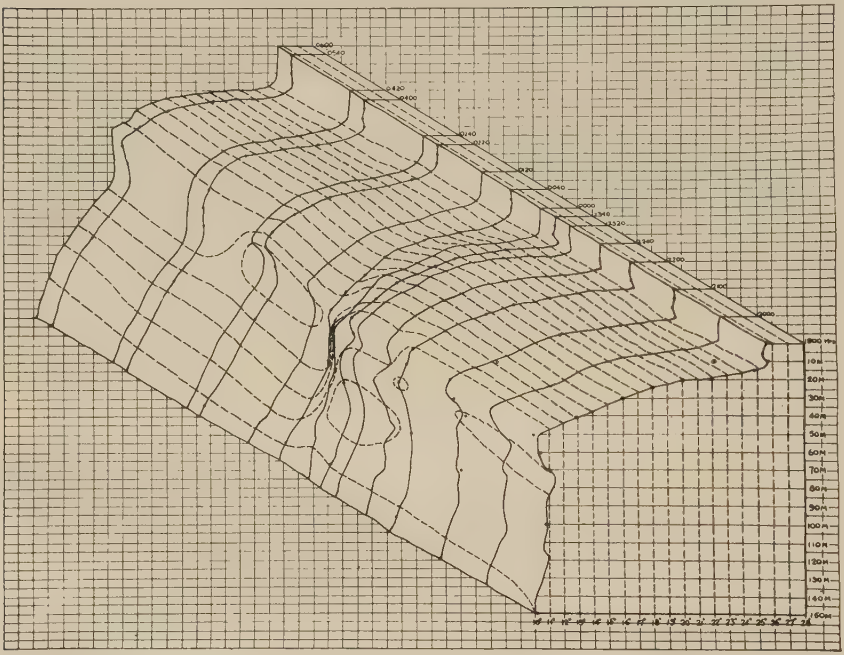


Figure 32. The variation of the temperature-depth profile with time, as determined from the bathythermograph traces and water bottle temperatures.

---

[2] This was actually the case. At Station no. 18 (Aug. 26, 1937, 2203 hrs.) of the cruise on which the instrument was tested the water bottles were spaced at 1, 5, 10, 15, 20, 40, 70, 150, 200, 300, and 400 meters and the smooth curve, drawn by Mr. C. O'D. Iselin through the points thus obtained, completely missed an abrupt change from the summer thermocline to isothermalcy which the bathythermograph indicated to exist at about 60 meters. Accordingly, at Station no. 19, one hour and forty minutes later in the same water, the spacing was altered to: 1, 5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 100, 150, 250, and 350 meters and the discontinuity of the thermal

(*c*) The sudden change in the character of the temperature depth curve below 50 meters between the hours 0000 and 0040 is very remarkable, for the "Atlantis" could not have drifted very far in this short space of time.[3]

(*d*) The traces shown at the following hours were taken with the bathythermograph. 1900, 2000, 2100, 2240, 2320, 0000, 0120, 0240, 0420, and 0600, while the curve obtained from water bottle thermometer readings are shown at 1900, 2100, 2200, 2340, 0040, 0220, 0400, and 0540. Thus, comparison between the bathythermograph readings and the thermometer readings may be made directly for the two times 1900 and 2100 when both series were taken nearly simultaneously. Such small differences (never more than 0.2° Centigrade) as are evident may easily be accounted for by the difference in time between the water bottle temperature station and the bathythermograph test.

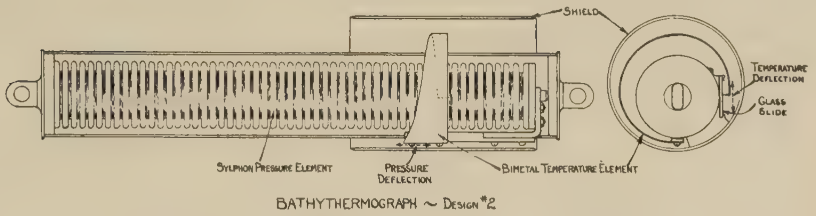


Figure 33. Design No. 2 for improved bathythermograph.

FURTHER DEVELOPMENT:

Though the result shown may be considered as very satisfactory, it is proposed to improve the instrument further by an attempt to utilize a design such as indicated in Figure 33. The improvement which such a design would incur is that the temperature element would be exposed directly to the flow of water and that all thermal lag by it would be eliminated. Furthermore, the size of the instrument, if constructed according to the design in Figure 33 will be cut down considerably and, though in the first design the coordinates are very nearly rectangular (because the length of the bi-metal strip is great compared to the deflection of its end), in the

---

gradient as indicated by the bathythermograph was established. The latter distribution of water bottles was thereafter maintained for subsequent stations in the same region.

[3] In a personal communication, Mr. Iselin informed the author that the T-S correlation also changes at the same time and, as the drift of the ship could not have been more than a mile or two, he concludes that the mixing in the neighborhood of 100 meters depth was very incomplete.

second design the coordinates will be perfectly rectangular. Finally it is thought that vibration will be entirely eliminated by the second design, and that, therefore, a finer trace and greater accuracy will be obtained.

It is hoped that this instrument can be produced, if demand is sufficient, cheaply enough to obtain it widespread application, not only by biologists and oceanographers, but also in the fishing industry—the apparatus being such that it can be handled by entirely untrained personnel.

Contribution No. 168

LIGHT PENETRATION IN THE CARIBBEAN SEA AND IN THE GULF OF MEXICO

By

GEORGE L. CLARKE

Biological Laboratories, Harvard University

and

*Woods Hole Oceanographic Institution**

The growing interest in the intensity of light beneath the surface of the ocean from both the physical and the biological points of view has resulted in further efforts to obtain reliable measurements under widely differing conditions and in a variety of locations. For the most part, however, these measurements have been made in northern waters and have been confined largely to coastal regions. There has resulted a paucity of precise observations in the tropical parts of the ocean. The work of Grein (1913–14) in the Mediterranean produced highly irregular results (cf. Atkins, 1932). Certain visual observations have been made by Beebe (1934) off Bermuda, and a small number of measurements were undertaken by Stephenson (1934) from a submarine off California. The work of Hulburt (1932) was confined to measurements of the absorption coefficients of samples of sea water brought into the laboratory.

To extend our knowledge of light penetration to the more southern parts of the North Atlantic, our photometric apparatus was placed aboard the research vessel "Atlantis" at the outset of her cruise to the Caribbean and the Gulf of Mexico during the winter of 1936–37. Measurements were carried out at every suitable opportunity, but because of the press of other work and the frequent occurrence of stormy weather, a much smaller number of series was completed than was hoped. The observations presented

---

* Contribution no. 168.

Reprint from SEARS FOUND. JOURN. MAR. RES.

below are therefore not to be regarded in any sense as a complete survey, but represent a first step in filling a serious gap in our knowledge of light conditions in tropical and sub-tropical waters.

The deck and sea photometers employing Westinghouse Photox Cells described by Powell and Clarke (1936) were used for this investigation. The spectral sensitivity of these cells exhibits a maximum at 5500A and drops off to 10% of the maximum at 4650A and 6250A. This relatively broad sensitivity admits of the criticism that the value obtained for the transparency of the water is a composite of the transmissive exponents of a large number of wave lengths, the relative intensities of which may differ with depth. However, since the logarithmic plots of measurements made in homogeneous bodies of water are remarkably straight, any such discrepancies must be of negligible proportion. It would appear that, in these cases at least, the most effective radiation at all depths centers about the same part of the spectrum.

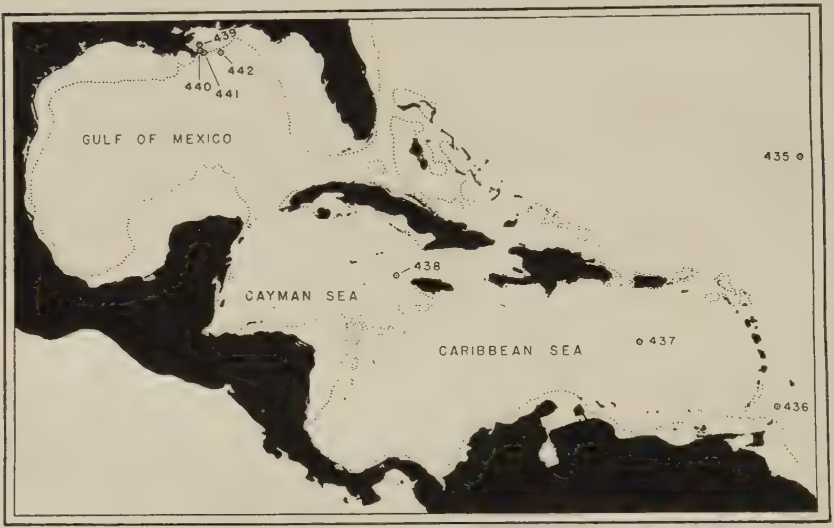


Figure 26. Map showing the locations of stations where light penetration measurements were made. The "Series Number" of each set of observations appears beside the circle representing the station.

The spectral band to which the present photometers are sensitive is essentially the same as that measured by the "green-sensitive" combination of filters and photoelectric cells employed by Oster and Clarke (1935). The spectral sensitivity of the Photox cells corresponds so closely to that of the human eye that we may refer to the light measured as the visible part of the total solar radiation. Furthermore, since approximately the same spectral sensitivity appears to characterize the photosensitive organs of marine animals generally (Clarke, 1936a), the reduction of light indicated by our instruments as they are lowered into the sea is presumably the same as that perceived by a fish or other animal sinking a corresponding distance in the water.

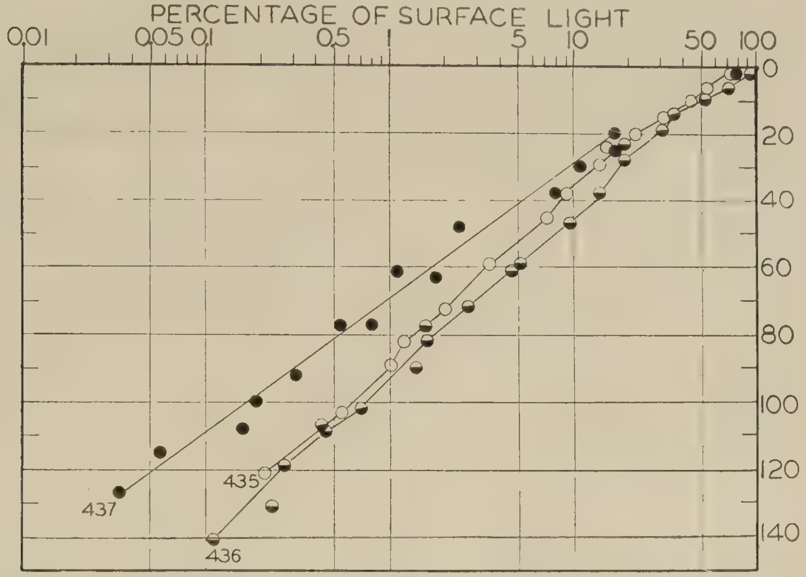


Figure 27. Relation between depth and irradiation expressed as a percentage of the light just over the surface (logarithmic scale). Series numbers indicated at end of each curve.

Series	Locality	Latitude	Longitude	Date	Time (E.S.T.)	Sky*	Sea	Wind†
435	Antilles Current	24°00′N	59°03′W	Jan. 4, 1937	09:50–10:44	bc	moderate	3–4
436	No. Equatorial Current	12°04′	60°29′	Jan. 12, 1937	10:55–11:45	o	rough	4–5
437	Caribbean Sea	15°20′	67°10′	Jan. 26, 1937	10:00–10:42	bc	moderate	4–5

* U. S. Weather Bureau symbols. † Wind force on Beaufort Scale.

The same procedure was followed and the same precautions observed in making these light penetration measurements as has been described previously. I am indebted to Mr. Alfred Woodcock for carrying out the observations at sea and to Mr. David Bonnet for assistance in preparing the figures.

The location of each series of measurements is shown in Fig. 26. Series 435 was made in the Antilles Current at a distance of about 900 miles SE of Bermuda. Series 436 was located in the Northern Equatorial Current just East of the Lesser Antilles. Series 437 and 438 were made respectively in the center of the Caribbean Sea and in the Cayman Sea* just West of Jamaica. Series 439 to 442 were made in the Gulf of Mexico East of the Mississippi Delta at different distances from shore.

TABLE I

Comparison of Average Values of the Transmissive Exponent, k,* for the "Green" Component of Daylight for the Depth Ranges Indicated

Series	*Station*	*Locality*	*Ranges (meters)*	*k*	*Total Range (meters)*	*k*
307	2243	Sargasso Sea, N of Bermuda	—	—	5–92	.050
311	2245	Gulf Stream, N of Bermuda	—	—	5–136	.049
415	2484	Gulf Stream, S of Grand Banks	2–10	.082		
			10–95	.057	2–95	.059
435	2726	Antilles Current	2–20	.068		
			20–121	.045	2–121	.049
436	2748	Northern Equatorial Current	2–14	.079		
			14–141	.045	2–141	.048
437	2803	Caribbean Sea	20–130	.058†		
438	—	Cayman Sea, W of Jamaica	2–95	.045		
			95–185	.038	2–185	.042
439	—	Gulf of Mexico, E of Mississippi Delta	2–25	.22		
440	—	Gulf of Mexico, E of Mississippi Delta	2–20	.19		
			20–53	.10		
441	—	Gulf of Mexico, E of Mississippi Delta	2–6	.16		
			6–24	.088		
			24–81†	.058†		
442	—	Gulf of Mexico, E of Mississippi Delta	2–95	.054		
			95–169	.039	2–169	.047

* In the equation $I/I_0 = e^{-kL}$ where L is the thickness of the water layer (in meters) in which the intensity is reduced from I_0 to I.

† Approximate.

The transparency of the water at the station in the Antilles Current (Series 435) and at the station in the Northern Equatorial Current (Series 436) was found to be uniform over the ranges measured, as is attested by the straightness of the logarithmic plots (Fig. 27), although the upper strata tended to be somewhat less transparent than the deeper layers (Table I). The water in these areas is known to be highly homogeneous from a hydrographic point of view (Iselin, 1936; Parr, 1937), and at the time of the present observations the temperature change from the surface to a depth of 150 m. was only about 4° C. Since the average values of the transmissive exponents for these series (k = .049 and .048 respectively) are so nearly the same, we may conclude that there was practically no difference in transparency at these two localities.

---

* Name proposed by Parr (1937) to designate the body of water between the Gulf of Mexico and the Caribbean Sea proper (see Fig. 26).

The observations in the Caribbean Sea (Series 437) unfortunately occurred during unfavorable weather conditions with the result that the measurements are rather widely scattered. However, a straight line connecting the value at 20 m. with that at 130 m. appears to form a satisfactory average curve for the whole series below 20 m. The slope of this curve gives a value of k = .058. Although individual measurements above 20 m. were unreliable, the transparency was evidently considerably reduced in the upper stratum. The temperature at the surface was 26.0° C. and at 150 m. was 19.8° C. at this station.

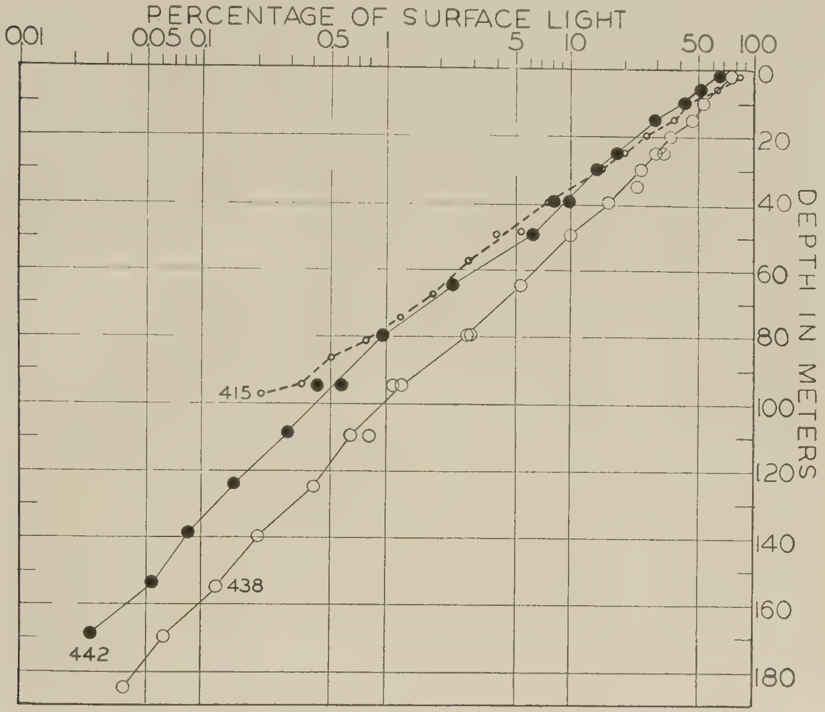


Figure 28. Relation between depth and irradiation expressed as a percentage of the light just over the surface.

Series	Locality	Latitude	Longitude	Date	Time	Sky	Sea	Wind
415	Gulf Stream (S of Grand Banks)	39°56′N	48°40′W	Sept. 15, 1935	15:35–17:00 (L.A.T.)	o	slight	3–4
438	Cayman Sea	18°38′	79°12′	Feb. 28, 1937	10:45–12:42 (E.S.T.)	bc	smooth	1
442	Gulf of Mexico	29°14′	87°48.5′	April 11, 1937	10:30–11:18 (C.S.T.)	b	smooth	1

Since the measurements at the station in the Cayman Sea (Series 438) were made under favorable conditions, and since the values obtained are so consistent, we may place considerable reliance upon them. The series extended to a greater depth (185 m.) than has ever been reached previously with photoelectric or rectifier cell photometers. The curve for this series (Fig. 28) shows that the water at this locality was extremely uniform in transparency as would be expected from the hydrography (Parr, 1937). From 95 m. to 185 m. the value of the transmissive exponent was found to be $k = .038$. This water is therefore the most transparent (in respect to the "green" component of daylight) ever reported (cf. Oster and Clarke, 1935) and approaches the clearness of distilled water (for which $k = .024$ at wave length 5400A according to Sawyer, 1931). If we assume that the optical properties of the water at this station are the same as those of the Sargasso water off Bermuda, which is similar hydrographically, we may conclude that the "blue" component of daylight penetrates even more effectively than the "green" in this locality and therefore, that "blue" light is of measurable intensity at an even greater depth.

The region east of the Mississippi Delta was unfortunately the only part of the Gulf of Mexico where there was opportunity to make light penetration measurements. The four series of observations here were made in increasing depths of water and show how the effect of the muddy Mississippi water diminishes at increasing distances from shore (Fig. 29). The water in Series 439, where the depth was 25 m., was quite homogeneous and gave an average transmissive exponent of $k = .22$. This water was therefore approximately as turbid as Vineyard Sound or Provincetown Harbor (cf. Clarke, 1936b). In Series 440 (depth 63 m.) we see that a distinct change in transparency occurred at 20 m. Above 20 m. the water was only slightly more transparent than at the previous station but below 20 m. the value of the transmissive exponent was reduced to one half ($k = .10$).

The measurements composing Series 441 were made under conditions causing the ship to drift more than usual. The values obtained down to 40 m. appear sufficiently consistent to be reliable but below 40 m. the points are seen to scatter widely. At these greater depths the wire supporting the submarine photometers departed by as much as 60° from the vertical, making a precise determination of the depth of each observation difficult. Incorrect estimation of depth due to wire angle is a dangerous source of error in all deep readings and should be carefully guarded against. In this case the last measurement of the series was made with the photometer actually resting on the bottom. As a result the depth could be independently and accurately determined by means of the ship's fathometer and was found to be 81 m. A straight line has been drawn on the plot (Fig. 29) from the value obtained at this depth to the value found at 38 m. This (dashed) line may serve as an approximation for the illumination below 40 m. The complete curve shows that the water in the upper six meters was still highly turbid (k = .16). A transition layer occurred from 6 to 24 m. (k = .088). Below 24 m. the water was considerably more transparent (k = .058) than at the previous station.

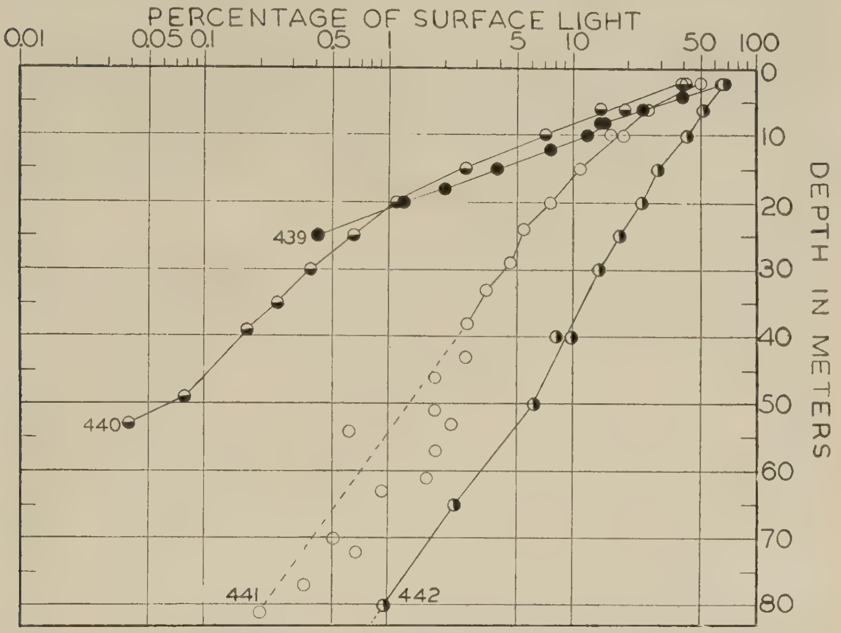


Figure 29. Relation between depth and irradiation expressed as a percentage of the light just over the surface.

Series	Locality	Latitude	Longitude	Date	Time (C.S.T.)	Sky	Sea	Wind
439	Gulf of Mexico	29°27′N	88°48′W	April 9, 1937	11:34–11:54	b	slight	3
440	Gulf of Mexico	29°16′	88°50′	April 9, 1937	15:30–15:53	bc	slight	3
441	Gulf of Mexico	29°08′	88°39′	April 10, 1937	10:45–11:30	b	slight	3
442	Gulf of Mexico	(See Fig. 3)						

Series 442 was made in 656 m. of water and under much more favorable weather conditions. A comparison with the other measurements in this region (Fig. 29) reveals a further great increase in transparency at this point. There is no evidence of relatively opaque water near the surface. However, a slight change of slope occurs at 95 m. (Fig. 28) giving transmissive exponents of k = .054 and k = .039 respectively for the curve above and below 95 m. Since the water at this station was almost as clear as that at the station in the Cayman Sea (Series 438), it appears that the effect of the muddy water from the Mississippi does not extend far in this direction from the Delta. At this point of observation, only some seventy miles from the nearest mouth of the river, the water had a transparency practically equal to the clearest ocean water known. The explanation of this apparent paradox lies in the fact the water debouching from the Mississippi is carried almost entirely to the west (Parr, 1935, Fig. 10). In speaking of the influence of the Mississippi and the other northern drainages, Parr says (loc. cit. p. 62): "This freshening influence, however, stays confined to the bank and does not seem to affect the surface layer over the deeper waters at all, even where the bank is quite narrow as at the mouth of the Mississippi itself. It will be noticed from our map of surface salinities that the freshening influence spreads westward and has very little effect to the east of the Mississippi Delta." Our measurements of transparency support these conclusions.

For the purposes of comparison three previous measurements made in Sargasso water (Series 307, 311, and 415) have been included in Table I and the curve of Series 415 has been added to Fig. 28. These observations taken together with the deep-water series reported in the present paper provide a general picture of transparency for a large part of the western North Atlantic in which oceanic water of high salinity exists. It is seen that the transparency throughout this whole region is extremely high and quite uniform. A gradual, though slight, decrease in transparency does occur from the Cayman Sea (Series 438) to a point in the Gulf Stream, south of the Grand Banks (Series 415), as is revealed by the increasing values of the average transmissive exponents (Table I and Fig. 28). However, the ratio of the highest average value of the exponent to the lowest is only .059 (Series 415)/.042 (Series 438) = 1.4. The extreme change over the whole length of the area (over 2000 miles) is accordingly only 40% in contrast to changes of 600% (for the corresponding "green" component of daylight) found by Clarke (1936b) in passing off-shore from Woods Hole toward Bermuda. Since in the latter case measurements in the turbid coastal waters are included, the two situations are not really comparable. However, most of the investigations of light penetration made heretofore—such as those of Poole and Atkins, Pettersson, and Utterback—have given a picture of great variability. The present observations are the first in which opportunity has arisen to study the transparency of a considerable oceanic area and, in this case, show a wide and uniform distribution of extremely clear water.

SUMMARY

Measurements of light penetration using Photox rectifier cells were made at 8 stations in the Caribbean Sea region and in the Gulf of Mexico. At the stations in shallow water east of the Mississippi Delta, considerable turbidity was encountered in the surface layers. But at the offshore station in the Gulf and at all the other stations the water was found to be highly uniform and extremely transparent. The value of the transmissive exponent from 95 to 185 m. at the station in the Cayman Sea west of Jamaica was $k = .038$,—indicating the presence of the clearest ocean water ever measured.

REFERENCES

ATKINS, W. R. G.
1932. Solar radiation and its transmission through air and water. Journal du Conseil, vol. 7, no. 2, August, p. 171–211.

BEEBE, W.
1934. Oceanographic work at Bermuda of the N. Y. Zoological Society. Science *80:* 495.

CLARKE, G. L.
1936a. On the depth at which fish can see. Ecology *17:* 452–456.

CLARKE, G. L.
1936b. Light penetration in the western North Atlantic and its application to biological problems. Rapports et Procès-Verbaux. Con. Perm. Intern. Exp. Mer. *101*, Pt. 2, p. 3–14.

GREIN, VON KLAUS
Untersuchungen über die absorption des lichts in seewasser. Monaco, Inst. Oceanog. Ann. 1913. I. Tome 5, Fascicle 6, 23 pp. 1914. II. Tome 6, Fascicle 6, 21 pp.

HULBURT, E. O.
1932. On the penetration of daylight into the sea. Journ. Optical Soc. of Am. vol. 22, no. 7, p. 408–417.

ISELIN, C. O'C.
1936. A study of the circulation of the western North Atlantic. Papers in Physical Oceanography and Meteorology (Mass. Inst. Tech. and Woods Hole Ocean. Inst.) vol. 4, no. 4, 101 pp.

OSTER, R. H. AND CLARKE, G. L.
1935. The penetration of the red, green, and violet components of daylight into Atlantic waters. Journ. Optical Soc. of Am. *25:* 84–91.

PARR, A. E.
1935. Report on hydrographic observations in the Gulf of Mexico and the adjacent Straits made during the Yale Oceanographic Expedition on the "Mabel Taylor" in 1932. Bulletin of the Bingham Oceanographic Collection (Yale University) vol. 5, Art. 1, 93 pp.

PARR, A. E.
1937. A contribution to the hydrography of the Caribbean and Cayman Seas. Bull. of the Bingham Oceanographic Collection (Yale University) vol. 5, Art. 4, 110 pp.

POWELL, W. M. AND CLARKE, G. L.
1936. The reflection and absorption of daylight at the surface of the ocean. Journ. Optical Soc. of Am. *26:* 111–120.
SAWYER, W. R.
1931. The spectral absorption of light by pure water and Bay of Fundy Water. Contr. Can. Biol. and Fisheries. N. S. vol. 7, no. 8, p. 75–89.
STEPHENSON, E. B.
1934. Absorption of light by sea water. Journ. Opt. Soc. of Am. *24:* 220–221.

Contribution No. 169

PRESENT STATUS OF THE PROBLEM OF SUBMARINE CANYONS *

H. C. STETSON

Research Associate in Submarine Geology, Woods Hole Oceanographic Institution

About three quarters of a century ago J. D. Dana (1), by commenting on the existence of a trough lying off the mouth of the Hudson River, may be said to have put before the geological world a problem to which we still do not possess the answer. His data were the relatively rough charts, to judge by their present day successors, furnished by the U. S. Coast and Geodetic Survey at that period. As more of these curious gashes were discovered in various parts of the world, geological discussion was stimulated, although on the older charts the form of the valleys was necessarily shown only as vague indentations in the continental slope (2, 3, 4). Here the matter rested for some years.

The recharting of Georges Bank by echo sounding was the spark which revived the question. For the first time a really adequate picture of the configuration of the valleys was available. It is hard to overestimate our debt to the U. S. Coast and Geodetic Survey for the continued development of this new technique, and for its application to offshore, deep-water surveying. Today we know the shape of these valleys with considerable exactness, we know their distribution, in some cases we know their age, but when the word origin is mentioned geologists can be counted on to line up in two opposing camps. It is not so much their size and world wide distribution which is disturbing, it is the as yet unanswerable problems to which they give rise. In order to account for their origin we are faced with the necessity of altering the relationship of land and sea to a seemingly

---

* Contribution No. 169 of the Woods Hole Oceanographic Institution.

PROCEEDINGS OF THE AMERICAN PHILOSOPHICAL SOCIETY,
VOL. 79, NO. 1, APRIL, 1938
Reprint *Printed in U. S. A.*

impossible extent, or else appealing to submarine currents. It is becoming apparent, from the data which modern physical oceanography is accumulating, that the forces governing currents in the present-day oceans are not those which could produce the special types required for this work. A bottom current of a radically different type, brought into existence by the peculiar conditions of the Pleistocene, has been postulated by Daly. This will be discussed later. Some of the canyons have been dated by means of fragments of fossiliferous rock dredged from their walls, and they are found to be relatively young. Obviously erosional processes on a grand scale were in operation only yesterday, but the clues are just as obscure as though the cutting had taken place in the Cambrian.

The multiplicity of the theories and the extraordinary variety of processes, which have been called upon to produce the desired result, give ample testimony that the problem of canyon origin possesses no ready solution. The proposals range all the way from the interference of celestial bodies to density currents of an exceedingly complicated type. Let us now review the chief explanations which have been offered in the light of what little factual evidence we possess.

Before the charts of the recent surveys had been published, many considered the valleys to be tectonic rather than erosional features (5, 6). It is conceivable that a few of them can be explained in this way, but in every instance where an adequate survey has been carried out such has proved not to be the case. Faulting and folding never produce valleys of this shape, and they are certainly not the lunate scars of landslides. Most people will agree that they could only have been formed by running water, but where, under the air or under the sea? (7, 8.)

The advocates of subaërial origin have two alternatives. The land can be elevated or sea level can fall. Now that the maximum age of the canyons is known, the first hypothesis has developed so many obvious difficulties that it has few adherents today. The extensive grading and general adjustment to present sea-level which the continental shelves display the world over, indicate that they are features of considerable antiquity. The canyons which notch their margins are so similar in general configuration and depth that contemporaneous formation is suggested. Consequently, under this hypothesis, it is necessary to infer that since the late Tertiary, the continental margins have been simultaneously elevated a matter of 10,000 feet or more, that they stayed there a short time, and then sank again to approximately the original level. The affect of such an enormous uplift on pre-existing drainage would have to be obliterated in the same short interval, since no record of any such dislocation remains.

Lowering sea level also has its drawbacks. It has been suggested that the bottom of one or more of the ocean basins sank and then returned to its former position, much like a piston in a cylinder. At present this point is safely beyond the reach of argument, for no one knows anything about the bottom of any one of the major ocean basins.

Hess and MacClintock (9) would change the shape of the hydrosphere, possibly by retarding the rotational speed of the earth, although they admit the difficulties of finding a satisfactory cause. Could this be effected, sea level would of course fall, below a certain critical latitude, with a consequent rise above it. They start with the premise that no canyons are found polewards of latitudes 55° to 60°. It has been argued however that 35° and not 55°–66° is really the nodal point (10, 11). If this is so, the hypothesis breaks down, for plenty of canyons are known north of 35°, and for that matter south as well.

One more method of lowering sea level has been suggested —the Pleistocene ice sheets. The commonly accepted estimate of the reduction of sea level by this means is of the order of 300 feet. Shepard (12), however, by enlarging known areas of ice accumulation, assuming an average thickness of four miles for the whole sheet, and chiefly by postulating an ice cap for the polar basin, raises the estimate to what the conservative considers the almost astronomical figure of 3,000 feet. We have no yardstick to serve as a basis for discussion of much that he proposes. However, there are several factors in connection with the formation of an Arctic ice cap which deserve mention. This cap, to have any effect on sea-level, would have to extend to the bottom, a distance of two miles or more. Otherwise accumulating snow and ice on the surface would only sink the sheet deeper in the ocean, thereby displacing more water. Furthermore, the Arctic is today a region of little precipitation, and with a perpetually frozen ocean, surrounded by land masses covered with snow and ice, would it not be even more arid? At best accumulation would be thin compared to that farther south. In support of his hypothesis Shepard cites some recent work by the Russians showing that an ice sheet flowed southwards over northern Eurasia. However, the whole coast is bounded by an exceptionally wide continental shelf. The sea over this shelf is shallow, and, made even shallower during the Pleistocene by the withdrawal of water elsewhere, probably froze solidly to the bottom. Might not this platform be the center of accumulation for the southward flowing ice over Siberia?

Submarine currents of different types have frequently been suggested as the excavators of the canyons (13, 14, 15). In 1936, bottom currents in two of the Georges Bank canyons were measured by means of an Ekman meter (16). The normal, rotary system of tidal currents on the continental shelf is upset, and on the bottom the currents were found to flow up and down the valleys. Yet even here, where the currents at the surface are exceptionally strong, the highest recorded velocity was 11.08 cms. sec., or a little more than .2 of a knot at the peak of the flood tide. Spring tides at the surface have a velocity 40 per cent greater than the neaps, during the course of which the reading was made. If we arbitrarily increase this velocity by the above amount we get only 15.51 cms. sec. Considering the indurated nature of some of the beds of which this part of the continental shelf is composed, it does not seem probable that currents with velocities such as these would be particularly competent agents of erosion. They would move the finer grade sizes in an unconsolidated deposit, and by so doing might serve to check or retard present day deposition, but this is the most effective rôle which they can be expected to play. The tidal currents were strong enough to completely mask other types which may have developed an on and off-shore component, and it is to be expected, in coastal waters, that they will always have the greater velocities. We are justified therefore, in eliminating tidal currents from the list of factors responsible for the east-coast canyons, and it is probable that further work will show this to be true for all canyons.

As was stated above, modern physical oceanographers tend to look with disfavor on the theory that these canyons could have been cut by present-day currents or by currents in the past actuated by similar forces (17). Localized currents with a strong on and off-shore component would be required, and aside from tidal currents, it has not been demonstrated that any such exist. Furthermore the conditions necessary for their production and maintenance are not fulfilled by the data which are gradually accumulating.

Daly has argued for a radically different type of density current (18). During the times of lowered sea level of the Pleistocene, large areas of unconsolidated, fine-grained deposits on the continental shelf and slope, which formerly had lain below wave base, came within the reach of wave action. Large quantities of sediment were thrown into suspension by the storms of that period. This heavier, denser water would first seek the depressions of the shelf. It would concentrate in them and run down the slope with greatly accelerated motion. Sufficient velocity might be developed to cut grooves, and later, trenches. Daly also considers the possible erosive effect of submarine mud flows which might be set in motion by the drag of this current of muddy water on the bottom. In a recent paper, Kuenen strongly supports the idea (19). He finds, by tank experiments, that currents of this type will cut grooves in an unconsolidated "slope," and also that they do not diffuse readily with the surrounding water. There is no question but that this mechanism could operate in the open sea. The crux of the matter is, of course, the amount of energy available for the work translated in terms of velocities, and the hardness of the rocks which must be cut. The rocks of the Georges Bank canyons are known in more detail than those of any of the others (20). The upper part of the walls stand as cliffs with many outcropping ledges. The stratigraphic succession, as far as it is known, runs from the upper Cretaceous to the late Pliocene. A large proportion of these beds consist of clays, silts, and greensands which show little consolidation, but there are several beds of hard sandstone. Granite, as well as semiconsolidated sediments, has been reported from the walls of some of the California canyons (21). The presence of resistant rocks is the chief stumbling block which this theory has to overcome, and may prove a serious difficulty should many hard formations be found in future dredging.

The foregoing comments are not intended to be offered as purely destructive criticism, but to emphasize the point of view that there is no one universal explanation for the problem of canyon origin. The extreme differences of opinion which exist today are indications that in the future we will come to recognize a combination of causes. Also, it may well be that different canyons have been formed by different means. Should we assume a similar mode of origin for gorges cutting the seaward margin of broad, well-graded shelves; for those which head almost at the shoreline, and for those which lie at the outer end of a trench leading from some large river? Continued dredging and continued charting will help provide the answer. Without additional facts further discussion can not advance beyond the stage of hypothesis.

REFERENCES

1. Dana, J. D. Manual of Geology, Philadelphia, 1863, p. 441.
2. Upham, W. *Am. Geol.*, Vol. 10: 222–223, 1892.
3. Spencer, J. W. *Bull. Geol. Soc. Amer.*, Vol. 14: 1903, 207–226.

4. Hull, E. The Sub-Oceanic Physiography of the North Atlantic Ocean, London, 1912.
Sub-Oceanic Physical Features off the Coast of Western Europe. *Geog. Jour.*, Vol. 13, 1899, pp. 285–289.
5. Lawson, A. C. Origin of Carmelo Bay. Univ. of Calif. Dept. Geol., Bull. 1, 1893–1896, pp. 1–59.
6. Wegener, Alfred. Origin of Continents and Ocean Basins, Translated by I. G. A. Skerl, London, 1924 p. 178.
7. Shepard, F. P. Submarine Valleys. *Geog. Review*, Vol. 23, No. 1, Jan. 1933, pp. 77–89.
8. Shepard, F. P. Canyons off the New England Coast. *Am. Jour. Sci.*, Vol. 27, 1934, pp. 24–36.
9. Hess, H. H., and MacClintock, P. Submerged Valleys on the Continental Slope and Changes of Sea Level. *Science*, n.s., Vol. 83, April 3, 1936, pp. 332–334.
10. Shepard, F. P. Submerged Valleys on the Continental Slope and Changes of Sea Level. *Science*, n.s., Vol. 83, June 26, 1936, pp. 620–621.
11. Lambert, W. D. An Old Answer to a Present-Day Problem. *Science*, n.s., Vol. 86, July 23, 1937, pp. 79–80.
12. Shepard, F. P. The Underlying Causes of Submarine Canyons. *Proc. Nat. Acad. Sci.*, Vol. 22, No. 8, Aug. 1936, pp. 496–502.
13. Buchanan, J. Y. Land Slopes Separating Continents and Ocean Basins. *Scottish Geog. Mag.*, Vol. 3, 1887, pp. 217–238.
14. Lawson, A. C. The Continental Shelf off the Coast of California. *Bull. Nat. Research Council*, No. 44, Vol. 8, Pt. 2, 1924, pp. 3–23.
15. Davis, W. M. Submarine Mock Valleys. *Geog. Review*, Vol. 24, 1934, pp. 297–308.
16. Stetson, H. C. Current Measurements in the Georges Bank Canyons. *Trans. Amer. Geophysical Union*, 18th Ann. Meeting, 1937, pp. 216–219.
17. Iselin, C. Personal communication.
18. Daly, R. A. Origin of Submarine "Canyons." *Amer. Jour. Sci.*, Vol. 31, No. 186, 1936, pp. 401–420.
19. Kuenen, Ph. H. Experiments in Connection with Daly's Hypothesis on the Formation of Submarine Canyons. *Leidsche Geol. Mededeelingen*, Deel 8, Afleving 2, 1937, pp. 327–351.
20. Stetson, H. C. Geology and Paleontology of the Georges Bank Canyons, Pt. I, Geol. *Bull. Geol. Soc. Amer.*, Vol. 47, 1936, pp. 339–366.
21. Shepard, F. P. Continued Exploration of the Calif. Submarine Canyons. *Trans. Amer. Geophysical Union*, 17th Ann. Meeting, 1936, pp. 221–223.

Contribution No. 170

FLUCTUATIONS IN MONTHLY SEA LEVEL ON EASTERN U. S. COAST AS RELATED TO DYNAMICS OF WESTERN NORTH ATLANTIC OCEAN

By

R. B. MONTGOMERY

*Woods Hole Oceanographic Institution**

and

Massachusetts Institute of Technology

In the determination of the pressure and velocity distributions in the oceans, very little use has heretofore been made of the observations of sea level available from the many permanent tidal stations. Insofar as the tidal stations have been interconnected by accurate leveling surveys, such observations would aid in the determination of absolute pressure and velocity distributions. Even where the tidal stations are not so connected the variations observed may still be applied in studying fluctuations of pressure and velocity. The present paper constitutes a preliminary discussion of the causes of sea level fluctuations and an exploratory investigation intended to reveal the extent to which it may be profitable to apply tidal station observations of sea level to the oceanography of the western North Atlantic.

Of the numerous permanent tidal stations available the representative stations chosen, as being apparently relatively independent of coastal influences and as being of prime importance with regard to the dynamics of the current system, were Bermuda, Charleston, Miami and Key West. See Figure 67. The stations further north are mostly located in inland waters such as Chesapeake Bay, and even the more exposed ones such as Atlantic City are flanked by a fairly broad continental shelf and are still further separated from the main current system, the Gulf Stream, by a wide band of slope water which is not free from gradient currents; hence they are omitted from this preliminary analysis. Monthly values of sea level for the four stations listed above were kindly made available by the Director of the Coast and Geodetic Survey, U. S. Department of Commerce. I have expressed these as departures from mean sea level and changed the unit to the centimeter.

Since it is desired to determine the pressure field in the water, the effect of variations in atmospheric pressure has been eliminated from the sea level departures by adding the monthly barometric departures from normal

---

* Contribution No. 170.

Reprint from SEARS FOUND. JOURN. MAR. RES.

for the respective stations, expressed in centimeters of water. This correction rarely amounts to more than 4 cm. Monthly atmospheric pressures for Charleston, Miami and Key West were from "World Weather Records" and the *Monthly Weather Review;* those for Bermuda were supplied in manuscript by Lieutenant Commander H. B. F. Moorhead. The resulting reduced monthly values of sea level are given in Tables 1–4. The mean monthly values formed from these tables are plotted in Figure 68.

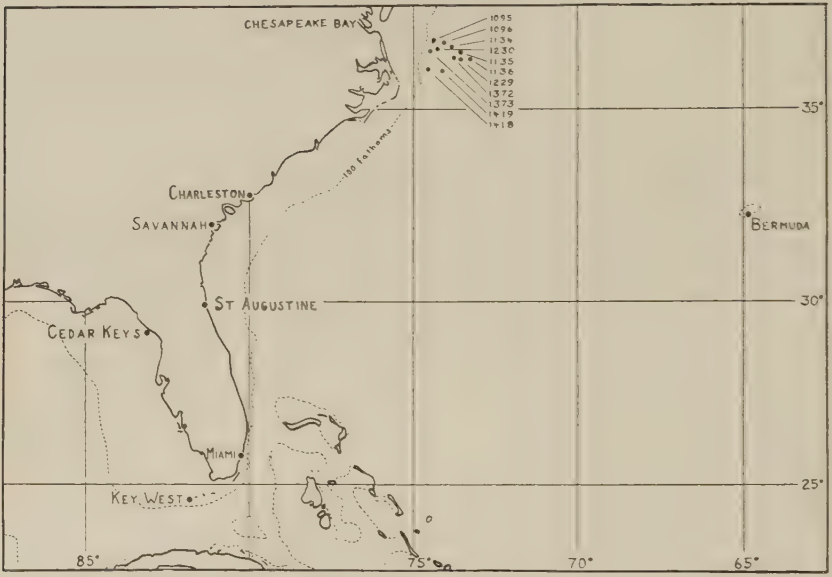

CHESAPEAKE BAY
1095
1096
1134
1230
1135
1136
1229
1372
1373
1419
1418
35°
100 fathoms
CHARLESTON
SAVANNAH
BERMUDA
ST AUGUSTINE
30°
CEDAR KEYS
MIAMI
25°
KEY WEST
85°
75°
70°
65°

Figure 67. Locations of stations.

COMPARISON OF VARIATIONS IN MONTHLY SEA LEVEL ON EASTERN U. S. COAST AND IN OFFSHORE SEA LEVEL CALCULATED FROM OCEANOGRAPHIC DATA

It is standard oceanographic procedure to compute space variations in the geopotential (dynamic height) of the sea surface from the observed sub-surface density distribution on the assumption that at a certain deep level there are no horizontal pressure gradients. Thus one arrives at the deviations of sea level from a level surface, or surface of constant geopotential. The usual unit for expressing geopotential is the dynamic centimeter, which for practical purposes has the same *magnitude* as the linear centimeter (the error is only the percentile deviation of local gravitational acceleration from 1000). The basis for assuming no horizontal pressure gradients at a deep level is that the motion there, so far as we know, is very slow. It is customary for deep-water calculations to assume an isobaric surface of 2000 decibars (approximately 2000 meters deep) or more as a level surface. If the deep isobaric surface is assumed to be at a *fixed* geopotential, time variations of sea level may be computed from time variations of density.

On four occasions throughout the year 1932 *Atlantis,* research vessel of the Woods Hole Oceanographic Institution, made hydrographic sections from Chesapeake Bay to Bermuda, taking temperatures and water samples to an average depth of 2100 meters. From the resulting density distributions Dietrich (*4*) has computed the elevations of the sea surface along the sections on the assumption that there are no horizontal pressure gradients in the oxygen minimum layer (250–950 meters deep). In order to obtain the height of the sea surface at the western end of the sections, where the bottom is shallower than the depth of the oxygen minimum, he has presumably assumed vanishing horizontal pressure gradients at the bottom. He has compared (abb. 15) the variation from section to section in computed height of sea level at the western end with observed monthly sea level at Atlantic City, finding rather good agreement without reducing the latter to normal atmospheric pressure.

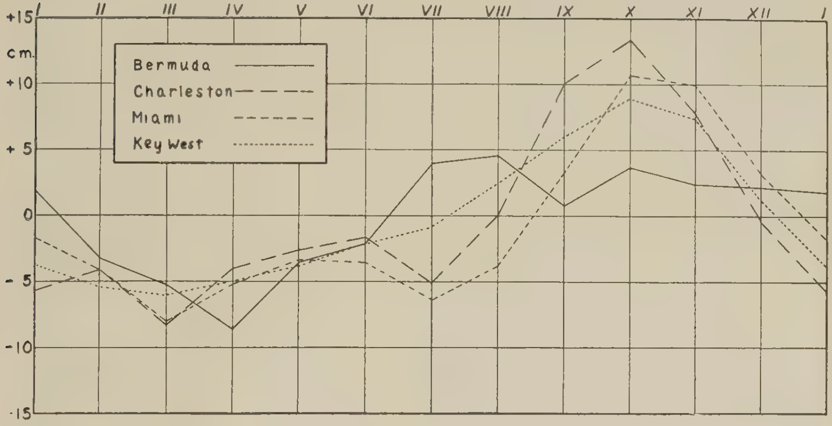


Figure 68. Annual variation of sea level reduced to normal atmospheric pressure.

Since the extrapolation involved in computing the elevation of the sea surface in shallow water is necessarily very unreliable, it appears to me better for the present purpose to use the height of the surface in the deep and comparatively stagnant body of water just outside the continental shelf (slope water), and to compare these computed fluctuations with monthly sea level at tidal stations relatively free from coastal influences.

Furthermore, the assumption that there are no horizontal pressure gradients in the oxygen minimum layer leads to gradient currents below this layer of the same order of magnitude as, but of opposite direction than, he finds for the surface of the Gulf Stream, a result which cannot be accepted.* Dietrich apparently now (*5*) acknowledges this criticism as just, and merely advocates the use of the oxygen minimum layer as a base level for computing the *relative* topography of isobaric surfaces. Accordingly the following recomputation is presented of the relation between fluctuations in sea level at tidal stations and those found oceanographically.

In order to eliminate as far as possible short-period oscillations, of about one day or less, as well as any observational inaccuracies, the average of two or three oceanographic stations is used to represent each occasion. From the four sections mentioned above I have used the same stations which Iselin (*8*) (p. 28) chose as representative of slope water conditions. A pair of stations made in the same region in October 1931 are also employed, making a total of five occasions. The positions of the stations are shown in Figure 67. The hydrographic data for these stations have been published in *Bulletin Hydrographique* (Appendice pour l'année 1931, and *Bulletin* pour l'année 1932).

Assuming the isobaric surface of 2200 decibars to be a level surface of fixed elevation, and assuming constant atmospheric pressure, the height of sea level has been computed from the vertical density distribution at each of these stations. The results are presented in the column designated H_a in Table 5, expressed in centimeters of dynamic height anomaly above 2200 db., which is the difference between the actual value and the dynamic height above 2200 db. for standard sea water of temperature 0°C. and salinity 35°/₀₀.

The mean of the five average values given in Table 5 may, for lack of further information, be regarded as representing mean sea level in the region considered. Likewise the values given in the last column of the table may be regarded as departures from mean sea level. The largest of the departures amount to 7 cm. This is about twice as great as the short-period oscillations Seiwell found at *Atlantis* station 2639 (180 miles northwest of Bermuda, maximum range during three days of 8 cm.). Hence, especially since the departures are based on two or three stations, it is unlikely that they are due to short-period oscillations. It is probable that they are largely associated with longer-period fluctuations, ones of between one week and one year.

---

* The possibility of a *weak* counter-current below the Gulf Stream is not doubted. While Dietrich's small slope of the sea surface across the Gulf Stream is not accepted, it may easily be that the slope resulting from using say the 2000 db. surface as a base level is too large.

Figure 69 shows the monthly values of sea level for two and a half years at Charleston and Miami, and the five oceanographic determinations. The latter show a good correlation with the tidal observations at both Charleston and Miami. The amplitude of the oceanographic variations is noticeably less than that found at Charleston, but is the same as that at Miami.

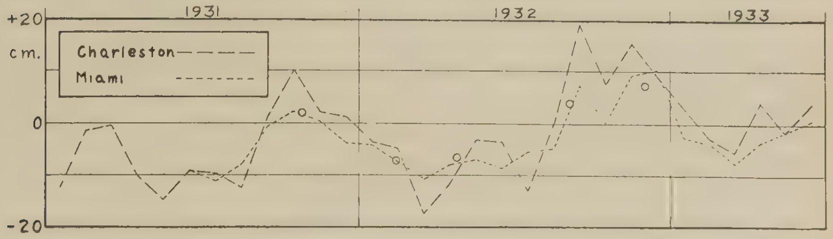


Figure 69. Monthly sea level reduced to normal atmospheric pressure at tidal stations, and five oceanographic determinations of sea level off Chesapeake Bay.

The agreement indicates that the tidal and oceanographic sea levels undergo a similar annual variation. It would not, however, be justifiable to conclude from this scanty material that deviations from the normal annual curve are similar in both sets of data. The apparent agreement shown by relatively low values in late 1931 and relatively high values in late 1932 is not altogether trustworthy, because the oceanographic value for October 1931 is based on two isolated stations instead of two or three stations chosen from a section crossing the Gulf Stream as in the other four cases, and because the western end of the section in late 1932 was somewhat further south than the other sections so that probably only station 1418 is representative of slope water conditions (cf. Iselin (*8*), p. 21).

CAUSES OF FLUCTUATIONS IN SEA LEVEL

The possible causes of long-period variations in sea level (reduced to normal pressure) at any station may be conveniently summarized as below*:

(1) *Dynamic* effects due to fluctuations in gradient currents.
(2) Effect of local winds or *Windstau.*
(3) *Local addition of mass.* This is especially effective in the tidewater of rivers, where sea level fluctuates with the river discharge. The effect of fresh water run-off is presumably negligible at the tidal stations discussed in this paper. It is also assumed that the addition

---

* A somewhat different classification may be found in Krümmel's "Handbuch" (*10*).

or subtraction of mass by precipitation and evaporation at the sea surface is so quickly equalized over large areas that it is of no significance locally with regard to fluctuations in monthly or weekly sea level. Change of total mass of oceans would become effective under (6).

(4) *Changes in configuration of ocean floor.* Alterations in a river channel affect sea level in its tidewater, but this is of no significance at the stations discussed in this paper. Earthquakes which alter the volume of the ocean basins would become effective under (6).

(5) *Atmospheric pressure.* The principal effect of fluctuations in atmospheric pressure is eliminated by the hydrostatic correction that has been applied to the tidal station observations. There is of course also a transient effect, but this would be of as short duration as the effect of rainfall mentioned under (3).* Application of the aforementioned correction involves the assumption that the average atmospheric pressure over the oceans is constant; this is nearly the case but introduces in the corrected values a variation amounting everywhere only to the variation in average pressure over the oceans (expressed as height of water).

(6) The *widespread* effects due to the action of any of the above at a distance or over large areas are placed together under this heading because at a given station they become indistinguishable. For lack of information this will not be discussed further.†

---

* The principal basis for the statements that addition of mass or increase of pressure at the surface are quickly equalized over large areas is the observed value of the "barometer factor," or average ratio of the departure from normal of sea level to the departure from normal in height of a mercurial barometer. The results for many stations give a mean value of the barometer factor which is very close to the negative of the density of mercury, indicating that there is very little lag in the adjustment of sea level to fluctuations in atmospheric pressure so as to maintain constant pressure at fixed points below the surface. For a recent brief summary concerning the barometer factor see Dietrich (*4*) (pp. 33–35).

† The action of (3), (4) and (5) in producing a widespread effect was discussed under those headings respectively. As an example of the action of (2) the following suggestion may be presented. Imagine a canal encircling the earth in the zone of westerly winds, and let there be a constriction at one part of the canal; sea level would be higher at the western end of this constriction than at the eastern end due to *Windstau.* This is essentially the case in the Southern Ocean and the constriction occurs at Drake Strait, sea level being higher on the Pacific side and lower on the Atlantic side (presumably!), accounting for the probable fact that the Pacific Ocean is generally at a higher level than the Atlantic. As a result of leveling surveys it has been found that "The average mean sea-level determination by tidal observations at Pacific Coast stations is about 0.5 meter higher than the average for the mean sea-levels at tidal stations for the Atlantic and Gulf Coasts." (*3*).

(7) *Thermal* effects.

  (a) *Local thermal* effects. If a given isobaric surface below the layer affected by seasonal temperature variations, say the 200 decibar surface, maintains constant elevation, then sea level must fluctuate in accord with the heat (and, included here as a factor which affects the density of sea water, fresh water) supplied or withdrawn at the surface.

  (b) *Advection.* Heat (and fresh water) may be supplied or withdrawn from a region by advection of different water masses. This refers especially to the condition maintaining coastal currents, the light water being supplied by fresh water run-off.

(8) *Astronomic tides* of long period.

It is probable that in the open ocean the long-period components of the *astronomic tide* approximate closely to the values given by the equilibrium tidal theory (*11*). The latter vanish at latitude 35° and have their maximum amplitudes at the poles as follows (the principal components only are listed and the values are for a rigid, ocean-covered earth; they are from Schureman (*16*), pp. 34, 55):

lunar fortnightly	4.1 cm.
lunisolar fortnightly	.2
lunar monthly	2.2
solar semiannual	2.0

The first three periods are of such length that they would not appear in the monthly means of sea level. Harmonic analyses for a few foreign stations give amplitudes for these three components considerably exceeding the theoretical values (Schureman (*16*), pp. 403–413), but these exceptional cases must be due to the effect of local topographical conditions on the astronomic tide. On the other hand a large semiannual component, as well as annual component which has no astronomic basis, are found at nearly all stations. At Charleston these are 9.4 and 7.4 cm. respectively. True tidal forces must therefore be of minor importance in explaining sea-level variations observed at well-exposed tidal stations.

Equilibrium tides would not produce any variations in the calculated dynamic height of the sea surface. The observed agreement between variations in dynamic height of the sea surface and in sea level at tidal stations therefore gives further evidence that the variations are not due to astronomic tides.

The *thermal* effect (produced locally or by advection) must be of importance in all temperate regions. This is substantiated by the fact that all of Marmer's (*12*) diagrams of the annual variation of sea level at tidal stations on the Atlantic and Gulf coasts of the United States (and the

Bermuda curve in Figure 68) have their maxima between June and October. At some other stations this effect is outweighed; Seattle's curve for example is below normal during April–October. The order of magnitude of the thermal effect is easily computed. An increase in temperature of the surface hundred meters from 8° to 18° at a salinity of 35°/₀₀ (roughly representing the change from February to July at the 100-meter contour off Chesapeake Bay according to Bigelow's diagrams (*2*)) would raise sea level by 19 cm. This is only slightly less than the range in sea level at Charleston shown in Figure 69, but the double maximum and the late occurrence of the chief maximum show definitely that the thermal effect is not the only one of importance.

Most writers on the subject of sea level fluctuations assume that the fluctuations are in large part due to *Windstau*, and find a close relationship with local winds. For instance Bergsten (*1*), from a comparison of monthly values of sea level at a number of tidal stations in Scandinavia and Denmark with the winds for each station, concluded definitely that all essential characteristics of the normal annual variations in sea level for those stations are caused by the local winds. Palmén, in his study of daily sea level and winds at Baltic stations (*14*), divided *Windstau* into two parts: the component of the slope of the water surface in the direction of the wind being pure *wind-effect* (*Windeffekt*), and the component at right angles being *stream-effect* (*Strömeffekt*). The latter is due to the longshore wind component, and can develop only to the extent that a longshore gradient current develops.* The gradient current is favored by a long straight coastline and by a wind that acts equally along the entire coastline. Hence this component of *Windstau* becomes to large extent indistinguishable from the dynamic effect.

For a rough indication of the annual variation of onshore wind in the vicinity of Charleston, use has been made of the monthly percentage frequency of wind direction at Savannah (*9*). Table 6 gives the average for the two periods 1891–1902 and 1923–1927 of the monthly frequencies of wind from NE, E and SE (first line), from SW, W and NW (second line), and the difference between these two (third line). This difference is intended to represent the net onshore wind. In the last line of the table are given the departures from normal of the net onshore wind. These are shown graphically in Figure 70, together with the annual variation of sea level at Charleston. The agreement between the two curves is striking. It must be remembered, however, that merely frequency of wind direction cannot give a complete description of the stress exerted by the wind on the water, especially since the latter is proportional to the second power of wind speed;* unfortunately a convenient compilation of velocities is not available. Further, both these curves bear a resemblance to the annual variation of the northeast trades (see last section), which are ultimately largely responsible for the Gulf Stream. It is safe to conclude that the wind plays an important rôle in the annual variation of sea level at Charleston, and that part of this is the direct effect of local *Windstau*, but it could not be definitely concluded that the whole, or even major part, of the sea level variation is due to local *Windstau*.

---

* The distinction between wind-effect and stream-effect, which are considered here for the stationary state of motion only, may be illustrated as follows. Along a *deep* coastline a normal drift current is set up with its transport cross-wind. An onshore or offshore wind produces no *Windstau*, but a longshore wind produces *Windstau* of stream-effect type which sets up a gradient current, the amount of *Windstau* being regulated by the gradient current. Along a very *shallow* coastline frictional forces entirely outweigh the Coriolis force; the drift current is down-wind and gradient currents cannot exist. An onshore or offshore wind produces *Windstau* of the wind-effect type, a longshore wind produces no *Windstau*. In water of intermediate depth, being the normal case, both types of *Windstau* occur simultaneously (except for directly onshore, offshore, or longshore winds).

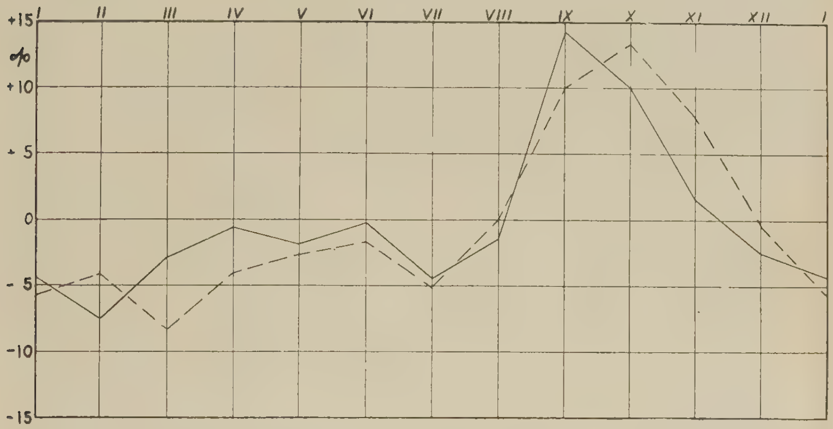


Figure 70. Full line: percentage frequency of net "onshore" winds at Savannah (from last row of Table 6). Broken line: annual variation of sea level at Charleston (reproduced from Figure 2).

The *dynamic* effect refers to fluctuations in sea level brought about by fluctuations in gradient currents.† A gradient current, as its name implies, requires a definite slope of the isobaric surface through each point (the slope depending only on the velocity, density and latitude at the point), and in the special case of surface gradient currents a definite slope of the sea surface is required. The dynamic effect, where the pressure distribution is produced by the motion, is to be clearly distinguished from the thermal effect, where the motion is produced by the pressure distribution. Fluctuations in sea level from the dynamic effect are to be thought of as due to fluctuations in surface gradient currents produced by forces acting on them before they enter (or after they leave) the vicinity in question.

---

* Some authors find the power to be less than 2, as for instance Palmén (*14*), but there can be no doubt that the power is considerably greater than unity.

† An interesting example of the dynamic effect, although it does not affect mean sea level, is its well-known action on a progressive tidal wave in a canal. High water and maximum flood at any point occur simultaneously, as do low water and maxi-

In the region here under consideration it is to be expected that considerable dynamic effect should occur due to fluctuations in the Florida Current or Antilles Current as they leave their source.*

As was mentioned above, it is difficult to distinguish between the local stream-effect of *Windstau* and the dynamic effect resulting from its simultaneous action in the surrounding regions. In the ocean, where the action of the stream-effect is essentially wide-spread, it would seem proper to call the immediate cause of the resulting sea level fluctuations *dynamic*, although the ultimate stream-effect cause is active in the same general region.

The good agreement of the fluctuations in sea level at the oceanographic stations off Chesapeake Bay with the fluctuations at Miami—even better than with those at the nearer station Charleston—indicates that, all along the left edge of the Florida Current and Gulf Stream from the Straits of Florida to beyond Cape Hatteras, sea level varies as a unit. This strongly suggests that the dynamic effect is of prime importance in producing these fluctuations. But how much of the dynamic effect is due to variations in the current before it reaches the Florida Straits, and how much to the action of winds after leaving the Florida Straits, cannot be said. At Charleston,

---

mum ebb. The dynamic effect on the tidal current produces a higher high water and a lower low water on one side of the canal than at the center, and a lower high water and higher low water on the other. For instance Marmer (*13*) has studied this difference in range for the Hudson River between Jersey City and lower Manhattan. Here the average surface current across the River at high and low water is 1.7 knots and the width 0.6 mile, giving a calculated difference in range of 0.06 foot (2 cm.), which compares favorably with the observed value of 0.08 foot.

* Since these two currents are in large part continuations of the Equatorial Current, it is of interest to mention Gallé's discussion of the rôle of fluctuations in the North Equatorial Current with respect to the annual variation of sea level observed at various tidal stations on the North Atlantic (*7*). He finds the annual variation of these two quantities closely correlated, using a time lag depending on the particular coastal region. His conclusion is that the former is not the cause of the latter, but rather that both find their direct cause in the atmospheric circulation around the North Atlantic high pressure area. This conclusion, however, cannot be regarded as final.

however, which is separated from the Gulf Stream by 50 miles of continental shelf, the monthly fluctuations are greater in magnitude (although the annual variation is of practically the same amplitude as at Miami), this increased amplitude being presumably due to local wind action.

FLUCTUATIONS IN SURFACE CURRENT DETERMINED FROM CROSS-STREAM GRADIENT OF SEA LEVEL

Regardless of the origin of the gradient currents it should be possible to compute, from sea level observed at two tidal stations separated by a body of water, the fluctuations in average surface gradient current normal to the line joining the two stations. This method was suggested by Sandström in 1903 (*15*), with especial regard to a line joining Iceland and the Norwegian coast.* But it is necessary to eliminate from the tidal station observations not only the barometric fluctuations, but also the wind-effect of *Windstau* and the effect of bottom friction on the currents near shore. These alter the sea surface near shore from the topography that would correspond to the currents, but outside the 200 meter bathymetric contour they have little effect if any.

From the agreement between the oceanographic and tidal-station determinations it may be concluded that this correction for Charleston is only a fraction of the total variation, say less than one half. As a first approximation it may be neglected altogether.

Bermuda is a station which, used in conjunction with Charleston, ought to make it possible to apply Sandström's method. An attempt was made to compare the tidal station data with the dynamic heights of the surface computed for oceanographic stations near Bermuda. Unfortunately the Bermuda tidal station was not established until November 1932, and since that time few oceanographic stations have been occupied in that vicinity. Dynamic heights computed for *Atlantis* stations within about 180 miles of Bermuda during 1931–1936 do not follow a regular annual variation nor do the ones since November 1932 agree with the monthly sea levels observed at Bermuda. This may be due to the fact that, as shown by the Chesapeake Bay to Bermuda sections figured by Iselin (*8*) (his Figs. 3–8, 10–11), the isolines of temperature and salinity have a considerable slope, usually upwards, towards Bermuda. Oft-repeated stations within a few miles of Bermuda would make it possible to gain some sort of a consistent picture of the relation between computed dynamic height of the surface and sea level observed at the tidal station.

If it is assumed, as was justified for Charleston, that sea level fluctuations observed at the Bermuda tidal station are roughly representative of the sea level fluctuations in deep water nearby, it may be that the difference of the monthly departures of sea level at Bermuda and at Charleston give a rough indication of the fluctuations of the average surface gradient current between Charleston and Bermuda. The difference Bermuda—Charleston has been taken from Tables 1 and 3 for each of the 47 months available and the monthly averages (after adding 2.8 cm. to reduce the normal to zero) are plotted in Figure 71 as the full line. This indicates that the average northward surface gradient current between the two stations has its maximum in July and minimum in October, with secondary maximum in January and minimum in April. Since sea level at Bermuda is about 80 cm. higher than at Charleston (calculated from the density distribution), the July and October values of +11 and −15 cm. represent deviations from normal of about 16%. Whether or not the associated fluctuations in current occur largely within the Gulf Stream cannot be said.

---

* So far as I know, the method has never been put into practice.

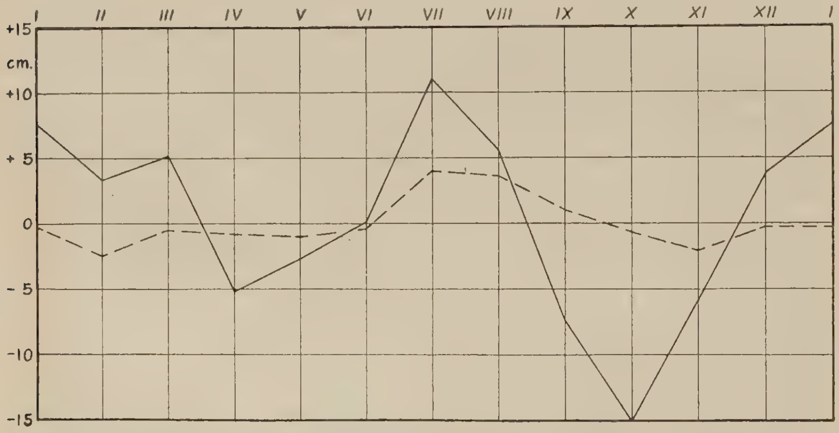


Figure 71. Annual variations of differences of sea level reduced to normal atmospheric pressure: full line for Bermuda–Charleston, broken line for KeyWest–Miami.

The results of the last paragraph are very uncertain. But it is clearly suggestive that an exact and useful application of the methods outlined may be possible if certain further observational material becomes available. At its source the Florida Current passes between Key West and Habana (Cuba), a distance of only 85 miles; further downstream it passes between Miami and the Bimini Islands of the Bahama group, a distance of only 50 miles. Since permanent tidal stations already exist at Key West and Miami, the establishment of stations at Habana and Bimini would make it possible, as Dietrich (*4*) (pp. 27–28) has already suggested, to apply this method of cross-stream gradient of sea level to two lines crossing the Florida Current.

FLUCTUATIONS IN SURFACE CURRENT DETERMINED FROM DOWNSTREAM GRADIENT OF SEA LEVEL

It has been found from leveling surveys that sea level is higher in the Gulf of Mexico than along the Atlantic coast. This head or difference in potential between the upstream and downstream ends of the Straits of Florida probably accounts for the major part of the energy of the Florida Current. On the assumption that the head accounts for all of the energy (i. e. that the Gulf of Mexico is a simple reservoir) and that the flow through the Straits is frictionless, the velocity at the downstream end of the Straits may be computed from Torricelli's theorem, $v = \sqrt{2\,gh}$ (v, g, h being velocity, acceleration of gravity, and head). The observed difference in level between Cedar Keys and St. Augustine is 19 cm. (*3*). These stations are rather far north from the Straits, and also their sea levels should be corrected as mentioned in the last section, but 19 cm. may be used as a rough value of the head. The resulting velocity is 193 cm. sec.^{-1}, which is close to the average velocity in the center of the Florida Current.

As a measure of fluctuations in head the difference of the monthly sea levels at Key West and Miami may be used. These should also be corrected, but the corrections are supposedly small due to the good exposures at these stations. The monthly differences taken from Tables 4 and 2 are shown in Table 7; this table also gives the mean monthly differences and in the last row these means reduced to a normal of zero. The last row is plotted as the broken line in Figure 71. (This curve is based on 67 monthly values, the Bermuda-Charleston curve on only 47.)

The maximum head occurs in July and the minima in November and February. Unfortunately no information concerning leveling between Key West and Miami has been published, so it is necessary to assume that the difference between these two stations is the same as between Cedar Keys and St. Augustine, namely 19 cm. On this basis the July and November values represent deviations from normal head of 16%. In terms of velocity this becomes 8%.

The Florida Current supplies part of the Gulf Stream, which in turn accounts for most of the surface gradient current between Charleston and Bermuda, so it is to be expected that the fluctuations in downstream gradient of sea level from Key West to Miami are related to the fluctuations in cross-stream gradient from Bermuda to Charleston. The agreement found in magnitude (8% and 16% in terms of velocity) and in character of the annual variation (Figure 71) is far from close, yet it is sufficient* to indicate the potential value of the two methods used and to lend weight to Table 7 as giving roughly the monthly deviations from normal in strength of the Florida Current. The mean monthly values shown in Figure 71 also resemble the strength of the northeast trades in the same or preceding month; some such relationship is to be expected since the trades provide the supply of water to the Gulf of Mexico as well as to the Antilles Current. For the trades in the region 15°–25° N. and 25°–40° W. Gallé (*6*) gives:

---

* The correlation coefficient between 47 monthly values of Bermuda—Charleston and Key West—Miami is + .32 ± .09 (second term is probable error). But Charleston and Miami are quite similar, and the correlation between Bermuda—Miami and Key West—Miami would be + .50 if the three stations were entirely independent and

month	*I*	*II*	*III*	*IV*	*V*	*VI*	*VII*	*VIII*	*IX*	*X*	*XI*	*XII*
wind in m.p.s.	5.5	5.2	4.6	4.7	5.8	6.2	6.1	5.3	5.3	4.5	4.6	4.7

In conclusion it is to be recommended that permanent tidal stations be established at Habana and Bimini,* and that Miami and Key West be included in the network of precise leveling. With the further use of suitably planned oceanographic observations and of the orginal records from coastal meteorological stations it should be possible to gain a fairly complete knowledge of the causes of the sea level fluctuations in the region discussed in this paper. This knowledge could be used to determine accurately, from tidal and meteorological observations alone, the fluctuations in the surface velocity of the Florida Current.

---

the fluctuations had the same standard deviations. Actually the latter correlation has the value + .49 ± .07. Hence at first sight it does not appear that cross-stream and downstream components of sea level lead independently to similar fluctuations of the current. However, the following analysis indicates that the coefficient + .49 is significant.

In the case of three series of numbers a, b, c the correlation between a–c and b–c depends merely on the standard deviations of a, b, c and the three individual correlations between them. Let a represent Key West, b Bermuda, and c Miami. In the present case the standard deviations are *not* the same, but are

$$\sigma_a = 7.08 \text{ cm.}, \quad \sigma_b = 7.26, \quad \sigma_c = 7.74,$$

and the correlation between Key West and Miami is *high*, namely $r_{ac} = +.887$. If there were no significance in the correlation between a–c and b–c it would have the value given by assuming b entirely independent of a and c, namely

$$r = \frac{\sigma_c^2 - \sigma_a\sigma_c r_{ac}}{\sqrt{(\sigma_a^2 - 2\sigma_a\sigma_c r_{ac} + \sigma_c^2)\,(\sigma_b^2 + \sigma_c^2)}} = +.30.$$

But the actual coefficient +.49 is significantly larger.

* The Woods Hole Oceanographic Institution, with the cooperation of the Coast and Geodetic Survey, has just established a permanent tidal station on Cat Cay, one of the Bimini Islands, which was set in operation on March 1, 1938.

SUMMARY

1. Variations in the dynamic height of the sea surface observed on five occasions during 1931–1932 in the slope water on the left side of the Gulf Stream off Chesapeake Bay are found to agree closely with monthly sea level reduced to normal atmospheric pressure observed at Charleston and Miami.

2. The possible causes of these long-period fluctuations are discussed and it is concluded that only the following can be of importance:

(1) *Dynamic* effect due to variations in gradient currents, in particular the Gulf Stream
    (a) caused by variations in the Florida Current and Antilles Current at their source.
    (b) caused by the action of wind (stream-effect).
(2) *Windstau* (wind-effect).
(6) *Widespread* effects.
(7) *Thermal* effects.

It may be concluded tentatively that (1) and (7) are of most importance for Miami and for the deep-water variations, while (2) also exerts a large influence at Charleston.

3. Means are discussed for determining fluctuations in the average surface velocity, especially of the Florida Current, merely from observations at tidal stations of the cross-stream gradient of sea level and from meteorological observations.

4. Similar means are discussed using the downstream gradient of sea level. A preliminary application of this method results in the monthly values in Table 7, which give a rough indication of fluctuations in the Florida Current.

REFERENCES CITED

1. Folke Bergsten.
1931. The annual fluctuation of the sea-water stage on the coasts of Scandinavia and Denmark. *Geografiska Annaler*, 13: 197–240.

2. H. B. Bigelow.
1933. Studies of the waters on the continental shelf, Cape Cod to Chesapeake Bay. *Papers in Physical Oceanography and Meteorology*, 2, No. 4 (see Figs. 10, 41, 44).

3. William Bowie.
1936. The place of geodesy in geophysical research. *Transactions of the American Geophysical Union*, Seventeenth Annual Meeting, pp. 15–20.

4. Günter Dietrich.
1937. Die Lage des Meeresoberfläche im Druckfeld von Ozean und Atmosphäre mit besonderer Berücksichtigung des westlichen Nordatlantischen Ozeans und des Golfs von Mexico. *Veröffentlichungen des Instituts für Meereskunde an der Universität Berlin*, Neue Folge, A, Heft 33, pp. 1–52.

5. Günter Dietrich.
1937. "Die dynamische Bezugsfläche," ein Gegenwartsproblem der dynamischen Ozeanographie. *Annalen der Hydrographie und Maritimen Meteorologie,* 65: 506–519.

6. P. H. Gallé.
1915. On the relation between departures from the normal in the strength of the trade-winds of the Atlantic Ocean and those in the water level and temperature in the northern European seas. Koninklijke Akademie van Wetenschappen te Amsterdam, *Proceedings of the Section of Sciences,* 17: 1147–1158

7. P. H. Gallé.
1926. On the relation between wind or current and mean sea level in the Indian and the Atlantic oceans and the adjacent seas. Idem, 28: 905–918.

8. C. O'D. Iselin.
1936. A study of the circulation of the western North Atlantic. *Papers in Physical Oceanography and Meteorology,* 4, No. 4.

9. W. Köppen und R. Geiger.
1936. Handbuch der Klimatologie. Verlag von Gebrüder Borntraeger, 2: J234–J235.

10. Otto Krümmel.
1907. Handbuch der Ozeanographie. Verlag von J. Engelhorn, Band I, pp. 55–63.

11. Horace Lamb.
1932. Hydrodynamics. Cambridge University Press, 6th ed., p. 362.

12. H. A. Marmer.
1927. Tidal datum planes. U. S. Department of Commerce, Coast and Geodetic Survey, *Special Publication* No. 135 (see Figs. 28–31).

13. H. A. Marmer.
1935. Tides and currents in New York Harbor. Idem, No. 111 (see pp. 67–68).

14. Erik Palmén.
1932. Über die Einwirkung des Windes auf die Neigung der Meeresoberfläche. Societas Scientiarum Fennica, *Commentationes Physico-mathematicae,* 6, No. 14.

15. J. W. Sandström.
1903. Ueber die Anwendung von Pegelbeobachtungen zur Berechnung der Geschwindigkeit der Meeresströme. *Svenska Hydrografisk Biologiska Kommissionens Skrifter,* 1.

16. Paul Schureman.
1924. A manual of the harmonic analysis and prediction of tides. U. S. Department of Commerce, Coast and Geodetic Survey, *Special Publication* No. 98.

17. H. R. Seiwell.
1937. Short period vertical oscillations in the western basin of the North Atlantic. *Papers in Physical Oceanography and Meteorology,* 5, No. 2 (see p. 31).

TABLE 1

Departures from Normal in cm. of Monthly Sea Level at St. Georges, Bermuda, Reduced to Sea Level Pressure of 1018.0 mb.

(Normal sea level is the average for 1933–1935, being staff reading of 4.19 feet; zero on staff is 8.95 feet below Bench Mark 1.)

Month	*I*	*II*	*III*	*IV*	*V*	*VI*	*VII*	*VIII*	*IX*	*X*	*XI*	*XII*
1932	—	—	—	—	—	—	—	—	—	—	− 1.0	− 1.7
1933			− 3.1	−13.6	− 3.6	+ 9.3	0.0	−10.2	− 6.4	+ 9.2	+ 2.2	+ 0.6
1934	− 0.4	− 3.7	− 8.3	− 6.7	+ 3.1	− 8.4	+ 6.0	+21.4	+13.3	− 5.5	− 0.9	+ 7.8
1935	+ 9.3	+ 2.3	+ 0.9	− 6.8	− 1.8	− 0.6	+ 2.9	+ 4.9	− 3.6	+ 0.2	+ 0.3	+ 4.4
1936	− 3.6	− 8.6	−10.1	− 7.5	−11.7	− 8.8	+ 6.9	+ 2.4	0.0	+10.8	+11.6	—
Means	+ 1.8	− 3.3	− 5.2	− 8.6	− 3.5	− 2.1	+ 4.0	+ 4.6	+ 0.8	+ 3.7	+ 2.4	+ 2.2

TABLE 2

Departures from Normal in cm. of Monthly Sea Level at Miami Beach Reduced to Sea Level Pressure of 30.04 inches

(Normal sea level is the average for 1932–1936, being staff reading of 3.42 feet; zero on staff is 9.48 feet below Bench Mark 6.)

Month	*I*	*II*	*III*	*IV*	*V*	*VI*	*VII*	*VIII*	*IX*	*X*	*XI*	*XII*	*Year*
1931	—	—	—	—	—	− 8.9	−11.1	− 7.8	− 0.5	+ 2.3	+ 0.4	− 3.7	—
1932	− 4.1	− 7.4	−10.8	− 8.0	− 6.9	− 8.5	− 5.5	− 4.8	+ 7.6	+ 0.3	+ 9.5	+10.5	− 2.3
1933	− 2.5	− 3.6	− 7.7	− 3.6	− 1.4	+ 0.7	− 4.6	− 0.6	+ 3.0	+19.3	+15.9	− 2.6	+ 1.0
1934	− 2.7	− 7.6	− 8.9	− 5.8	− 8.3	− 4.8	− 6.7	− 3.9	+ 3.5	+13.2	+ 7.4	+ 1.3	− 1.9
1935	+ 4.2	− 0.6	− 2.9	− 0.8	− 6.8	− 4.1	− 5.8	− 4.8	− 3.2	+16.1	+18.0	+ 4.2	+ 1.1
1936	− 3.2	− 1.5	− 9.9	− 7.7	+ 6.7	+ 4.4	− 4.6	− 0.8	+ 9.5	+12.8	+ 8.9	+ 9.3	+ 2.0
Means	− 1.7	− 4.1	− 8.0	− 5.2	− 3.3	− 3.5	− 6.4	− 3.8	+ 3.3	+10.7	+10.0	+ 3.2	—

TABLE 3

DEPARTURES FROM NORMAL IN CM. OF MONTHLY SEA LEVEL AT CHARLESTON REDUCED TO SEA LEVEL PRESSURE OF 30.07 INCHES

(Normal sea level is the average for 1922–1936, being staff reading of 4.96 feet; zero on staff is 14.22 feet below Bench Mark 1.)

Month	*I*	*II*	*III*	*IV*	*V*	*VI*	*VII*	*VIII*	*IX*	*X*	*XI*	*XII*	*Year*
1921	—	—	—	—	—	—	—	—	—	+13.6	+ 7.2	+ 3.0	—
1922	− 7.1	+ 0.9	− 1.4	− 2.7	+ 0.7	− 0.1	− 3.6	− 1.9	+18.1	+10.0	+ 7.9	− 6.2	+ 1.2
1923	− 4.4	− 0.7	−10.4	− 2.7	+ 2.9	− 3.7	− 7.1	−10.6	+ 3.5	+14.4	+ 8.7	− 6.5	− 1.4
1924	− 9.9	− 2.6	−11.5	− 6.8	−10.9	− 7.3	− 0.7	+ 3.2	+18.0	+23.3	+ 9.6	− 0.5	+ 0.3
1925	+ 6.6	− 0.2	− 1.3	+ 0.8	+ 0.7	+ 1.8	− 0.2	+12.9	+10.3	+ 0.2	+10.3	−12.3	+ 2.5
1926	−16.9	−21.7	−16.1	− 9.8	− 5.8	− 2.5	− 4.7	+ 2.5	+17.1	+ 6.9	− 2.1	− 3.8	− 4.7
1927	− 8.7	−11.8	− 0.2	+ 0.7	− 6.0	+ 1.4	− 6.1	− 1.1	+ 3.0	+ 4.5	+ 4.5	+ 1.6	− 1.5
1928	−19.5	−10.2	− 9.6	− 8.9	+ 0.5	− 8.4	− 4.0	+ 3.7	+ 8.4	+17.8	+ 8.7	+ 8.7	− 1.1
1929	−13.3	+ 1.9	−10.7	− 4.9	− 3.9	+ 8.4	+ 0.5	− 1.1	+11.9	+ 6.2	+ 7.4	− 7.2	− 0.4
1930	+ 9.9	+ 3.0	−15.1	− 0.9	− 7.8	− 3.7	−10.5	− 0.6	− 3.7	+13.8	+ 4.3	− 4.1	− 1.3
1931	−12.6	− 1.5	− 0.5	−10.4	−14.7	− 9.0	− 9.8	−12.5	+ 1.5	+10.2	+ 2.2	+ 1.3	− 4.6
1932	− 3.4	− 4.6	−17.5	−11.5	− 3.1	− 3.5	−12.9	+ 0.3	+19.4	+ 7.7	+15.8	+ 9.4	− 0.3
1933	+ 3.2	− 2.8	− 5.5	+ 4.2	− 1.5	+ 3.7	+ 2.7	+ 9.1	+ 9.0	+23.2	+ 7.1	− 2.1	+ 4.2
1934	− 6.6	− 5.4	− 7.3	− 5.4	− 1.0	− 9.2	− 8.5	− 7.3	+ 7.8	+21.9	+ 6.5	+ 1.0	− 1.1
1935	+ 8.3	− 4.1	− 3.1	− 0.9	+ 1.3	− 1.0	− 5.0	+ 1.0	+10.7	+19.6	+21.7	− 1.3	+ 3.9
1936	−10.7	− 2.0	−14.2	− 0.5	+ 9.1	+ 8.7	− 6.1	+ 4.5	+16.7	+21.6	+ 4.2	+12.6	+ 3.7
Means	− 5.7	− 4.1	− 8.3	− 4.0	− 2.6	− 1.6	− 5.1	+ 0.1	+10.1	+13.4	+ 7.8	− 0.4	—

TABLE 4

Departure from Normal in cm. of Monthly Sea Level at Key West Reduced to Sea Level Pressure of 30.02 inches

(Normal sea level is the average for 1913–1936, being staff reading of 4.93 feet; zero on staff is 13.06 feet below Bench Mark 29.)

Month	*I*	*II*	*III*	*IV*	*V*	*VI*	*VII*	*VIII*	*IX*	*X*	*XI*	*XII*	*Year*
1913	− 4.4	− 1.9	− 5.2	− 0.8	− 1.3	+ 2.0	+ 0.4	+ 6.9	+ 6.0	+ 7.3	+ 3.6	− 1.2	+ 1.0
1914	− 5.3	− 9.2	−11.4	− 7.9	+ 6.0	+ 1.2	− 4.3	+ 8.3	+10.3	+ 1.5	+ 2.3	+ 2.2	− 0.5
1915	− 1.6	− 2.2	− 4.6	− 5.2	− 9.9	− 5.7	− 3.3	− 1.1	+ 7.9	+ 8.5	+ 5.7	− 3.4	− 1.2
1916	− 3.0	− 2.5	− 9.9	− 7.2	− 1.8	− 7.6	− 0.7	+ 2.1	+ 6.2	+13.4	+10.9	+ 0.2	0.0
1917	− 7.6	− 4.3	+ 8.2	+ 2.4	− 1.3	− 2.4	− 4.6	− 5.3	+ 8.7	+16.3	+18.6	+ 7.9	+ 3.0
1918	− 5.4	− 9.6	− 5.4	− 0.4	+ 0.6	− 4.4	− 1.7	+ 2.0	+ 3.6	+ 1.5	+ 5.4	+ 4.3	− 0.8
1919	− 6.1	−11.4	− 4.1	− 7.7	− 8.4	− 2.0	+ 0.7	+ 2.3	+ 6.3	+12.4	+ 8.2	+ 1.3	− 0.7
1920	− 8.3	− 6.3	−18.5	−12.2	− 8.2	− 1.0	+ 0.7	0.0	+ 4.4	+ 7.3	+ 4.9	− 0.6	− 3.2
1921	− 1.6	− 5.5	− 3.2	0.0	− 1.4	+ 4.1	+ 0.4	+ 1.9	+10.5	+11.4	+ 3.2	+ 0.3	+ 1.7
1922	− 6.1	− 0.4	− 1.4	− 3.0	− 3.9	− 0.1	+ 4.2	+ 2.7	+ 8.4	+ 6.2	+ 3.4	− 4.6	+ 0.4
1923	− 3.9	− 4.7	− 2.3	− 2.3	− 0.2	− 1.7	− 4.4	− 4.0	+ 2.2	+ 4.1	+ 2.0	− 6.8	− 1.8
1924	− 5.4	− 3.8	− 7.8	−14.2	−10.9	− 4.6	+ 1.7	+ 4.6	+ 6.3	+ 8.2	+ 7.9	− 9.5	− 2.3
1925	− 7.7	− 4.0	− 6.4	−14.5	− 4.3	− 3.9	− 2.6	+ 3.7	+ 5.8	+ 5.1	+10.4	+ 1.1	− 1.4
1926	− 9.6	−16.0	−14.7	− 8.2	− 8.1	− 5.7	− 5.2	+ 5.8	+ 7.8	+10.3	+ 4.6	− 2.1	− 3.4
1927	+ 0.1	− 1.6	− 1.2	− 2.7	− 3.7	− 1.3	− 3.6	+ 2.8	+ 0.7	+ 6.8	+12.1	+ 4.1	+ 1.0
1928	− 4.1	−15.4	−10.4	−11.6	− 5.7	− 2.0	+ 0.9	+ 4.2	+ 5.4	+ 9.7	+ 9.6	+ 5.5	− 1.2
1929	− 7.6	− 1.8	− 6.5	− 0.9	− 1.4	− 2.1	+ 3.0	+ 3.1	+ 3.6	+ 3.7	+ 1.6	+ 2.5	− 0.2
1930	+ 3.8	+ 1.6	− 4.9	− 2.4	− 1.4	− 3.9	− 0.2	+ 6.0	+ 2.6	+ 8.6	+ 4.3	− 3.5	+ 0.9
1931	−10.7	− 9.1	− 4.4	− 4.4	−14.6	− 7.4	− 5.7	− 3.4	+ 3.7	+ 3.8	+ 5.6	+ 0.8	− 3.8
1932	+ 0.4	− 6.3	− 9.3	− 6.3	− 3.8	− 4.2	− 0.6	+ 2.1	+ 6.3	+ 5.1	+ 9.8	+11.6	+ 0.4
1933	+ 0.2	− 2.1	− 7.5	− 1.8	+ 1.3	+ 4.3	+ 2.4	+ 6.6	+ 9.0	+17.7	+13.8	+ 0.4	+ 3.7
1934	− 0.9	− 8.5	− 6.1	− 4.7	− 8.6	− 4.2	− 1.8	0.0	+ 9.2	+12.8	+ 8.2	+ 5.8	+ 0.1
1935	+ 4.5	− 3.3	− 0.2	− 0.3	− 4.1	− 2.6	+ 1.5	+ 4.7	+ 1.1	+17.5	+12.5	+ 2.4	+ 2.8
1936	− 2.0	− 1.2	− 7.8	− 4.8	+ 5.4	+ 4.7	+ 4.3	+ 3.4	+11.3	+17.1	+12.0	+10.8	+ 4.4
Means	− 3.8	− 5.4	− 6.0	− 5.0	− 3.7	− 2.1	− 0.8	+ 2.5	+ 6.1	+ 9.0	+ 7.5	+ 1.2	—

TABLE 5

Dynamic Height of Surface at *Atlantis* Slope Water Stations

Station	*Date*	*L* *North*	λ *West*	H_a *dyn. cm.*	*Average*	*Departure from 131*
1095	X, 25, 1931	36°41′	74°21′	136	133	+2
1096		36°38′	74°03′	130		
1134	II, 12, 1932	36°31′	73°50′	120	124	−7
1135		36°24′	73°29′	125		
1136		36°13′	73°16′	128		
1229	IV, 22	36°12′	73°32′	125	124½	−6½
1230		36°27′	74°15′	124		
1372	IX, 2	36°16′	73°46′	137	135	+4
1373	3	36°25′	74°28′	133		
1418	XI, 30	35°57′	74°32′	133	138½	+7½
1419	XII, 1	35°55′	74°07′	144		
				mean	131	

TABLE 6

Monthly Percentage Frequencies of Winds at Savannah

	I	*II*	*III*	*IV*	*V*	*VI*	*VII*	*VIII*	*IX*	*X*	*XI*	*XII*	*Mean*
NE–SE	9.5	8.3	9.7	10.0	9.7	10.3	8.7	10.7	18.5	16.3	12.0	10.0	—
SW–NW	16.5	18.5	15.3	13.3	14.2	13.2	15.8	14.8	6.8	8.8	13.2	15.2	—
Difference (net "on-shore" component)	−7.0	−10.2	−5.6	−3.3	−4.5	−2.9	−7.1	−4.1	+11.7	+ 7.5	−1.2	−5.2	−2.7
Departure from −2.7	−4.3	− 7.5	−2.9	−0.6	−1.8	−0.2	−4.4	−1.4	+14.4	+10.2	+1.5	−2.5	—

TABLE 7

Monthly Sea Level Difference in cm., Key West–Miami

(Values in Table 4 minus values in Table 2)

Month	*I*	*II*	*III*	*IV*	*V*	*VI*	*VII*	*VIII*	*IX*	*X*	*XI*	*XII*	*Year*
1931	—	—	—	—	—	+ 1.5	+ 5.4	+ 4.4	+ 4.2	+ 1.5	+ 5.2	+ 4.5	—
1932	+ 4.5	+ 1.1	+ 1.5	+ 1.7	+ 3.1	+ 4.3	+ 4.9	+ 6.9	− 1.3	+ 4.8	+ 0.3	+ 1.1	+ 2.6
1933	+ 2.7	+ 1.5	+ 0.2	+ 1.8	+ 2.7	+ 3.6	+ 7.0	+ 7.2	+ 6.0	− 1.6	− 2.1	+ 3.0	+ 2.6
1934	+ 1.8	− 0.9	+ 2.8	+ 1.1	− 0.3	+ 0.6	+ 4.9	+ 3.9	+ 5.7	− 0.4	+ 0.8	+ 4.5	+ 2.0
1935	+ 0.3	− 2.7	+ 2.7	+ 0.5	+ 2.7	+ 1.5	+ 7.3	+ 9.5	+ 4.3	+ 1.4	− 5.5	− 1.8	+ 1.7
1936	+ 1.2	+ 0.3	+ 2.1	+ 2.9	− 1.3	+ 0.3	+ 8.9	+ 4.2	+ 1.8	+ 4.3	+ 3.1	+ 1.5	+ 2.4
Means	+ 2.1	− 0.1	+ 1.9	+ 1.6	+ 1.4	+ 2.0	+ 6.4	+ 6.0	+ 3.4	+ 1.7	+ 0.3	+ 2.1	+ 2.4
−2.4	− 0.3	− 2.5	− 0.5	− 0.8	− 1.0	− 0.4	+ 4.0	+ 3.6	+ 1.0	− 0.7	− 2.1	− 0.3	—

Contribution No. 171

(Reprinted from The Collecting Net, Vol. XIII, No. 7, August 27, 1938)

THE INFLUENCE OF FLUCTUATIONS IN THE MAJOR OCEAN CURRENT ON THE CLIMATE AND THE FISHERIES

C. O'D. Iselin

Assistant Professor of Oceanography, Harvard University

Contribution No. 171 of the Woods Hole Oceanographic Institution

The relatively few physical oceanographers in the world would like nothing better than to be given time to develop the technical side of their studies, for there is a great deal still to be learned about the circulation of the ocean. However, of recent years this very young field of science has made good progress and as a result, there is increasing pressure on the hydrologist to put his investigations to some practical use. Would it not be possible, for example, by studying the Gulf Stream as it flows past this coast to predict a mild winter for northern Europe? Can the failure of a given year class of commercial fish sometimes be explained by sudden off shore movements of the coastal waters and are not these perhaps caused by variations in the strength of the main, deep oceanic currents?

It is such questions as these that the Royal Society had in mind when two years ago a special committee undertook to raise some money to develop the Bermuda Biological Station as an oceanographic base. The co-operation of the Woods Hole Oceanographic Institution was enlisted and a five year program of investigation has already been in progress for over a year. One satisfactory result of all this is that the Bermuda Laboratory has indeed received much needed financial support. The fact that a small research vessel has been provided by the Royal Society makes us hope that Bermuda will become more and more used by biological investigators. It is much less certain that the physical program, part of which will be outlined here, will come anywhere near the desired goal.

In studying the fluctuations of a major ocean current such as the Gulf Stream, it is of course necessary to secure observations over a considerable period of years before it can be said with certainty whether or not the current does have a significant annual variation in strength. Our temptation is to assume that it does. It may very well be that the Gulf Stream runs as steadily as a clock, in which case the various theories presented below have little practical application. However, it sometimes pays to speculate, and physical oceanography has now reached the stage in its development when speculation can be put on a reasonably sound physical basis.

The popular belief, of course, is that the Gulf Stream fluctuates quite widely in strength and position. The available modern observations indicate that this is certainly not correct. However, it can be said that the Gulf Stream probably has a tendency to vary in strength from time to time by about 10%. Perhaps even such slight fluctuations in the current can have quite far reaching consequences.

It is always easier to discuss a particular problem than to generalize. Therefore, the Gulf Stream will be used to illustrate the principles to be explained below. However, the Gulf Stream is only one part of the main North Atlantic anticyclonic eddy and each of the other oceans has a corresponding eddy. In other words, if our analysis of the problem in the case of the Gulf Stream is sound, the same principles can be applied to other parts of the world.

There are three main theories that have been advanced by scientists to explain the influence of the Gulf Stream on the climate and fishery of Northern Europe. In the light of recent oceanographic observations none of these theories is entirely satisfactory. Nevertheless, it will be worth while to state these theories for they constitute the background for the fourth and newest theory that is now being developed.

The oldest theory and the one most usually subscribed to simply assumes that the Gulf Stream resembles a river of warm water flowing northeastward towards the European coast and that it varies in strength from year to year. When the current is strong, sea surface temperatures will tend to rise off the Irish coast, for example, and if this trend persists, the climate will become milder. If the warm saline water floods in over the continental shelf or enters the North Sea in exceptional quantities, the fishery will be affected.

The chief difficulty with this theory is that as a transporter of warm water the Gulf Stream is in reality relatively ineffectual and that the greater part of the current does not flow towards the northeast, but curves around to the right towards the Azores and is there picked up by the northeast trades to continue in the anticyclonic eddy of the North Atlantic basin. A northern branch of the Gulf Stream, it is true, does carry some relatively warm water eventually to the Norwegian Sea. The fluctuations appear to be much greater in this northern branch than they are in the main eddy and, as will be argued presently, it may well be that even the relationship is reversed and that the northern branch strengthens when the Gulf Stream and the North Atlantic eddy weaken. In short, the early theory emphasizes the fact that from the European standpoint the Gulf Stream appears to be a variable current, but the theory is in too simple a form to be helpful without considerable modification.

The second theory which attempts to explain the variations in the temperature and salinity of the European coastal waters was advanced by a French oceanographer, LeDanois. This theory minimizes the importance of the Gulf Stream, but stresses the fact that from the European standpoint widespread invasions of warm water apparently occur from time to time. It is known as LeDanois' transgression theory.

LeDanois draws attention to the fact that on the whole the waters of the North Atlantic can be subdivided into two relatively independent parts on the basis of temperature and salinity. At the surface these two contrasting water-masses meet in a line extending roughly from the southern Grand Banks to the Faroe Islands. South of this boundary is found at the surface a wedge shaped layer of relatively warm water having salinities higher than 35%, the thickness of the wedge increasing towards the south. To the north and at all depths below the light saline water lies a much greater mass of colder water with salinities always lower than 35%. LeDanois believes that the wedge-shaped saline mass is not constant in position or volume. An expansion of the wedge towards the northeast he terms a transgression and a retreat of the warm water he calls a regression. He has found evidence that the transgressions occur in regular cycles having periods of 1, 4½, 9 and 18 years. The regularity of the cycles he attributes to astronomical causes.

Many objections can be raised against the details of the transgression theory and especially the modern oceanographic observations do not support LeDanois' assumption that the Gulf Stream does not continue east of the Grand Banks. Nevertheless, there is reason to believe that the warm saline water which from time to time seems to invade the European costal areas arrives more as a tongue than as a current. However, as yet there is little sound basis to the idea that the transgressions occur in regular cycles.

The third theory and perhaps the one in which fewest flaws can be found, is based on the assumption that the winds are the primary variable. During years when on the whole southerly winds prevail across the belt between the Grand Banks and Ireland, the surface layer will be shifted to the north and, therefore, at any one latitude sea surface temperatures will rise. In the same way, if winds with northerly components predominate, colder water will be brought into the critical area off the European coast. A general change in sea surface temperatures of only a few degrees produced in this manner should result in a significant climatic variation. Likewise an invasion of oceanic water over the fishing grounds might be caused by a few exceptional westerly gales. Unfortunately no suitable study has yet been made of the variability of the winds over the critical area between the Grand Banks and the Irish coast. All that we can say now is that if the winds are sufficiently variable, they probably are capable of producing fluctuations through shifts of the surface layer without necessarily upsetting the permanent deeper circulation. During a considerable part of the year the surface layer is well separated from the rest of the ocean by a sharp thermocline which may allow it to move quite independently.

We will return to the frictional effect of the wind, but first the newest theory, in which the strength of the whole North Atlantic eddy is considered the primary variable, will be discussed.

For this theory to be understood, it is necessary to have some knowledge of the general principles of Bjerknes' circulation theorem. In the first place, it must be realized that for any moving body to continue in a straight path in the geographical sense, it must be acted upon by a force that in the northern hemisphere pulls it to the left. In other words, because of the earth's rotation a given mass of water will follow the course of an inertia circle unless it experiences some other force. In ocean currents it is the pressure gradient that exactly counteracts the apparent deflection due to the earth's rotation. The pressure gradient and the fictitious deflective force are both at right angles to the direction of flow. Therefore, the current flows across the pressure gradient and not down it as would be the case if the earth were not rotating.

Since the diameter of an inertia circle varies with the velocity of the moving particle (and also with the latitude), in general the greater the velocity of a current, the greater must be the pressure gradient at right angles to its course. In the case of the Gulf Stream, for example, this means that as the current increases, the thickness of the warm water in the Sargasso Sea must also increase, and that as the current decreases, the warm layer on its right hand side must become shallower. In other words, in the main anticyclonic eddy of any ocean, the thickness of the warm central core will vary with the velocity of the surrounding circulation.

Now the main superficial, oceanic currents derive their energy from the anticyclonic wind systems of mid latitudes. If the strength of the winds vary, the circulation theorem demands that either the volume of warm water at the center will ave to change or the eddy must change in diaieter. With decreasing currents and, therefore, ecreasing pressure gradient, either the eddy will ave to expand or warm water will have to be ischarged. The third possibility, i.e., cooling at he center accompanying a decrease in the wind ystem, probably does not occur to any marked xtent. In the same way, a strengthening of the ddy will in theory result in a decrease in its iameter. This in brief is the underlying priniple of the fourth and newest theory concerning he influence of fluctuations in the major ocean urrents.

As mentioned already, the theory assumes that he strength of the North Atlantic eddy varies lightly from year to year. If this is so, then it an be argued that since the eddy is not free to xpand because of the limitations of the basin, a ecrease in strength of the Gulf Stream will be ccompanied by a discharge of warm water tovards the northeast. The amount of warm water vhich must be discharged as the result of a 0% decrease in transport by the currents is urprisingly large. A simple calculation will show hat in this event the northern tongue of warm vater that moves towards the European coast vill be strengthened by about 225,000 cubic kiloneters. In the same way, as the currents increase, he northern branch will be interrupted until this mount of warm water has accumulated in the argasso Sea. We have here a mechanism, it is elieved, that can explain how relatively steady urrents can cause quite wide variations in the emperature and salinity of the waters off the oast of northern Europe. As mentioned already, he relationship is quite the reverse from that opularly believed in. As the Gulf Stream dereases in strength the climate of Great Britian, or example, should become milder and her shores hould be bathed by relatively warm saline water. Vhen the Gulf Stream increases the reverse hould happen.

At the present time the Woods Hole Oceanoraphic Institution is cooperating with the Bernuda Biological Station to collect routine observtions that will prove which of the theories we ave mentioned is the correct one. If this can e accomplished, it is not beyond the bounds of ossibility to suggest that by means of a few imple observations the major trends in the Britsh climate and fishery could be forecasted.

Because of the prevailing westerly winds at the resent time it seems very improbable that the luctuations in strength of the Gulf Stream can ffect the climate of the eastern coast of the Jnited States. However, they may well influence ur fishery, especially northeast of Cape Hatteras. Df course, the fluctuations of the offshore curents are not the only cause of the success or failure of a given brood of young fish. The local hydrological situation can also play an important part. However, as will be explained below there are at least two mechanisms whereby the Gulf Stream can seriously disturb the waters over the continental shelf.

The first mechanism again involves the circulation theorem. It is chiefly important to bottom fisheries near the edge of the continental shelf. As the current increases in strength, the depth of the main thermocline on its left hand side must become less. When the current decreases, all the isotherms of this layer of relatively sharp vertical temperature gradient will lie deeper. Thus the bottom temperatures on the continental slope will vary with the strength of the Gulf Stream. At depths of about 200 meters a small change in the current can in this way result in a marked change of bottom temperature.

The second mechanism is less clearly understood and presumably it is most vital to the fish population just after the spawning period. It is a mechanism whereby a whole year class of fish can be wiped out completely in a few days.

One of the hydrographical problems which is very difficult to understand involves the tendency for coastal water to remain over the continental shelf. Our coastal waters are less dense than the offshore water. The prevailing wind is from the west. Why are our coastal waters not continually drifting out to sea? To take a specific case, why does Georges Bank water remain over the bank? If it drifted away, the whole population of young fish in the pelagic stage would be lost. As a matter of fact Walford, who has studied the plankton tows from 1932, finds that in that year practically all the young haddock were carried off the bank and consequently the 1932 year class is very weak in the present haddock population. Fortunately for the fishery such catastrophes do not happen frequently. If they did, no young fish could survive because all of the important commercial fish go through a planktonic stage when they cannot swim against the currents. This critical stage lasts from a few weeks to several months depending on the species.

The zone between the Gulf Stream and the 100 fathom curve is a mixing zone for coastal water and warm saline water that has escaped north of the Gulf Stream. The mixing agent is the eddies that are formed along the northern edge of the current. This zone with mixed water at the surface is called the slope water band. It extends from Cape Hatteras to the Grand Banks and averages 60 to 100 miles in width. The eddies in the slope water band seem to be of two main types. There is the type which persists for several weeks or months and which does not assimilate much coastal water. There is also the other type which is frictionally driven and in which can be observed a definite tongue of coastal water which is being sucked into the whirl. This type, apparently, is very dangerous to the fish population during its planktonic stage.

Since such an eddy also contains a tongue of warm saline water from the Gulf Stream, we are in hopes that the formation of these eddies is caused by fluctuations in the strength of the current and the necessity of a discharge of the warm water from the Sargasso Sea as mentioned previously. If this is the case such destructive eddies should be rare when the Gulf Stream is increasing in strength and should be common during years when the current is weakening. To this extent they will be predictable, and will perhaps explain why there is some correlation in the success and failure of year classes on the two sides of the Atlantic.

Finally to round out this whole topic, it is necessary to return to the frictional force of the winds on the sea surface. If it is assumed that this force is proportional to the wind velocity, then it seems unlikely that the ocean currents will vary significantly in strength from year to year. It is in low latitudes in the trade wind belts that the currents mainly receive their energy and, as is well known, the trade winds are comparatively steady. How can the strength of the major ocean currents vary in view of the relatively constant strength of the winds in low latitudes?

The recent studies of Rossby have pointed to a possible explanation. He has found evidence that there is a critical velocity below which the winds can get but little grip on the sea surface. If this critical velocity falls within the normal range of the trade winds, then it is clear how in certain years the currents can absorb much more energy than in others, even though the wind variation may be slight. To those who believe that the Gulf Stream is a variable current, this possible mechanism seems most significant. Therefore, it is part of the new cooperative program with the Bermuda laboratory to secure observations that can be used to determine the frictional force exerted by winds of different strength and duration. Likewise, it is planned to investigate the effect which the stability of the surface layer has on the wind current. Only in this way can it be proved whether or not the local winds off the European coast are as important to the climate and fishery as are the variations in the strength of the main circulatory system of the North Atlantic.

(This article is based upon a lecture given at the Marine Biological Laboratory on August 19).

Contribution No. 172

Reprinted from Biological Bulletin, Vol. LXXV, No. 1, 165–169, August, 1938
Printed in U. S. A.

A METHOD FOR MAINTAINING A CONTINUOUS SUPPLY OF MARINE DIATOMS BY CULTURE[1]

BOSTWICK H. KETCHUM AND ALFRED C. REDFIELD

(*From the Woods Hole Oceanographic Institution and the Biological Laboratories, Harvard University*)

Culture techniques by means of which large supplies of unicellular organisms can be continually available are greatly in demand. This is especially true of unicellular plants, since they are convenient organisms for the study of photosynthetic and other metabolic processes.

The problem is essentially one of the maintenance of a growing population. So long as no factors develop which limit the rate of multiplication, increase in a culture or population is directly proportional to the number of organisms present. The growth of the population is logarithmic during the initial period. Some factor or factors in the environment, however, sooner or later lower the division rate. These factors may be limiting nutrient concentrations, formation of inhibitory excretory products, production of non-viable cells in the process of division, or, in the case of photosynthetic plants, limiting light intensity.

It was pointed out by Hjort, Jahn and Ottestad (1933), in a study of whaling in the antarctic, that the most advantageous way to exploit a population is to keep it at the level at which the greatest number of new organisms are produced in unit time. This paper presents an application of this principle to a culture method. After procuring the cell concentration at which the greatest daily yield is obtained the culture is maintained at this concentration. A volume of culture containing the quantity of cells equivalent to the daily increase is withdrawn each day and is replaced by an equal volume of fresh sea water enriched with nutrients.

We have used the marine diatom, *Nitzschia closterium*, which is an ideal organism for a study of culture technique. It is a small cell which is readily maintained in pure bacteria-free cultures, and which remains freely suspended in the sea water medium.

The culture medium used was that devised by Miquel for freshwater diatoms, and modified by Allen and Nelson (1910) for marine forms. We further modified it by the addition of $MgSO_4$ to the enrichment solutions.

---

[1] Contribution No. 172 from the Woods Hole Oceanographic Institution.

Sea water was enriched by the addition of nutrients prepared as follows:

Solution A	KNO_3	20.2 grams/100 cc. water
Solution B	$Na_2HPO_4(12\ H_2O)$	4 grams
	$CaCl_2$	4 “
	$MgSO_4$	4 “
	$FeCl_3$ (melted)	2 cc.
	Conc. HCl	2 cc.
	dilute to	100 cc. with water

To each liter of sea water 0.55 cc. of solution A and 0.5 cc. of solution B were added. The reduction of the quantity of solution B from 1 cc. as used by Allen and Nelson to 0.5 cc. per liter was made in order to eliminate the precipitation of iron, magnesium and calcium phosphate which forms when larger quantities are used. The amount of solution A was adjusted to give the usual ratio of phosphate phosphorus to nitrate nitrogen in sea water. This ratio, as reported by Redfield (1934), is about twenty atoms of nitrogen to one of phosphorus.

In the culture of unicellular plants it is difficult to obtain sufficient light intensity without undesirable heating. Neon tubes obviate this difficulty since they radiate very little heat, and the emission is close to the optimum for chlorophyll synthesis. The apparatus finally devised consists of a U-shaped neon tube which is surrounded by a glass water-jacket 8 cm. in diameter. This is placed in the axis of a large cylindrical museum jar 21.3 cm. in diameter by 90 cm. in height. The culture occupies the space between the two cylinders. The neon tube is completely surrounded by the culture and little light is lost except that which passes through the medium without being absorbed. By regulation of the flow of water through the water jacket the temperature in the culture can be controlled. Air containing 5 per cent CO_2 is bubbled through the culture to maintain a large source of available carbon, and to keep the cells from settling. Nutrient solutions may be added to the culture from time to time by means of a dropping funnel.

In flask cultures of *Nitzschia closterium* in the above medium the growth is limited to 2×10^9 cells per liter by the complete exhaustion of nutrients. In the large culture nutrients are added when necessary and ten times the maximum cell concentration produced in flask cultures can be obtained. Every time a number of cells sufficient to exhaust the nutrients is formed the appropriate amounts of the nutrient solutions must be added. The necessity for enrichment may be determined by following the cell count or may be checked by periodical chemical analyses of the medium.

In Table I the data for the growth of a typical culture are presented. The division rate per cell is expressed by the velocity coefficient of the rate of growth, k. It is obtained from the equation

TABLE I

Growth of a culture of twenty-six liters of Nitzschia closterium with regular enrichment of the medium.

Time	Cell count	Division rate (k) per day	Daily yield
days	*cells/liter*		*cells/liter*
0	0.004 × 10^9	—	—
2	0.043 "	1.19	0.02 × 10^9
3	0.140 "	1.15	0.10 "
5	0.52 "	0.655	0.19 "
6	1.04 "	0.530	0.52 "
7	2.10 "	0.530	1.06 "
9	3.58 "	0.27	0.75 "
11	8.10 "	0.40	2.25 "
13	11.5 "	0.18	1.7 "
14	12.8 "	0.11	1.3 "
15	13.8 "	0.07	1.0 "

$$k = \frac{1}{t_2 - t_1} \cdot \ln \frac{C_{t_2}}{C_{t_1}}$$

in which C_{t_2} and C_{t_1} are respectively the cell concentrations at the end and beginning of the period under consideration. The division rate per cell remained approximately constant for the first three days of the culture period, after which it declined steadily.

The daily yield depends upon both the division rate and the cell concentration. It increased to a maximum on the eleventh day and then decreased. It is apparent that in order to obtain the maximum production of the culture it should be maintained at the cell concentration giving the optimum daily yield.

In Table II are given data procured by periodically reducing the cell concentration to the optimum by removal of the daily yield and subsequent dilution to the original volume. The values for the daily yield given in column five show that the production can be steadily maintained at its maximum. At the optimum cell concentration of 8 × 10^9 cells per liter 28 per cent of the total culture can be removed daily, giving a daily yield of about 2.4 × 10^9 cells per liter.

The total yield of a culture depends, of course, on its volume. The apparatus used in obtaining these data contained 26 liters, giving a total yield of about 62 × 10^9 cells per day. The dry weight of this quantity is approximately one gram. For the fifteen-day growth period of the culture (Table I) the average daily yield for the total period is only 24 × 10^9 cells per day. This value is only about one-third of that obtained by the renewal method after optimal conditions have been established and no continuous supply is obtained.

TABLE II

Yield of a culture of Nitzschia closterium maintained continuously at the optimal concentration for production.

Initial count	Final count	Duration of growth period	Division rate (k) per day	Daily yield
cells/liter	*cells/liter*	*hours*		*cells/liter*
8.84 × 10^9	11.36 × 10^9	25	0.243	2.42 × 10^9
7.70 "	11.15 "	41	0.217	2.02 "
8.10 "	12.92 "	45	0.250	2.57 "

This culture method was originally undertaken in an attempt to obtain diatoms for chemical analyses in quantities ranging up to a kilogram or more of dry material. The time required for producing such a quantity by this method could be reduced by increasing the number of units. A direct enlargement of the culture chamber is not desirable, since an increase in thickness of the culture would make the light intensity a serious limiting factor. A larger container could be used if it contained several light sources. A method for obtaining large quantities of diatoms directly from the sea has been described by Clarke (1937). Allen (1938) has recently criticized Clarke's method as being unnecessarily elaborate, but she does not appear to appreciate the magnitude of the quantities required, nor our need for a method applicable under those conditions of abundance frequently encountered in the sea.

The culture method described above has the advantage, not obtainable with natural collections, of producing a continuous supply of cells in a pure state. The culture can, moreover, be grown under various controlled environmental conditions and an ample quantity of material is produced daily for a variety of chemical and physiological tests. It is believed that a similar method can be applied advantageously to many other unicellular organisms required for physiological research.

BIBLIOGRAPHY

ALLEN, E. J., AND E. W. NELSON, 1910. On the artificial culture of marine plankton organisms. *Jour. Mar. Biol. Assn.*, **8**: 421–474.

ALLEN, W. E., 1938. Quantity collecting of plankton diatoms. *Science*, **87**: 171.

CLARKE, G. L., 1937. On securing large quantities of diatoms from the sea for chemical analysis. *Science*, **86**: 593–594.

HJORT, JOHAN, GUNNER JAHN AND PER OTTESTAD, 1933. Essays on population: the optimum catch. *Hvalrådets Skriffter*, Nr. 7, pp. 92–127.

REDFIELD, A. C., 1934. On the proportions of organic derivatives in sea water and their relation to the composition of plankton. *James Johnstone Memorial Volume*, Liverpool.

Contribution No. 174

Reprinted from BIOLOGICAL BULLETIN, Vol. LXXIV, No. 3, 376–394, June, 1938
Printed in U. S. A.

THE QUANTITATIVE VERTICAL DISTRIBUTION OF MACROZOÖPLANKTON IN THE ATLANTIC OCEAN BASIN[1]

BENJAMIN B. LEAVITT

(*From the Woods Hole Oceanographic Institution, Woods Hole, Massachusetts*)

During the summer of 1933 investigations were begun on the quantitative distribution of plankton with depth in deep water in the offing of Woods Hole, based on the volumes caught at different depths at levels two hundred meters apart (Leavitt, 1935). The present report is a continuation of this work. It also includes a partial analysis of the fauna which is responsible for variations in quantity at different depths.

LOCALITIES OF COLLECTION

The collections were made from the research vessel "Atlantis," at 9 stations, 100 to 300 miles south and east of Woods Hole (Fig. 1); precise localities and dates are given in Table I (p. 378).

Three of the ten stations (1733, 2263, 2462) were located in Sargasso Sea water, offshore from the Gulf Stream, one (1735) in the axis of the latter,[2] and six (1737, 1739, 2216, 2260, 2463, 2475) in the slope water inshore from the latter. These locations were chosen as representing oceanic conditions, all being well outside the continental edge, in deep water. One hundred and seventeen deep hauls were made, which may be dealt with from a quantitative point of view.

METHODS

The material was collected in closing-nets, either 1 meter or 2 meters in diameter, operated as earlier described (Leavitt, 1935). The releasing device (Fig. 2) has subsequently been improved to overcome the difficulties which arose with earlier models. It is made of phosphor-bronze and is hinged so that it may be opened to place it (on the cable) around a clamp which is bolted to the cable to prevent the releasing device from sliding up and down. The toggle bars to which the bridles are attached are so shaped as to obviate any danger of their failing to swing out and drop the bridles, when released. The messengers, also, are hinged to facilitate placing them on the cable, and locked in place by a pin. The proper functioning of the net depends on the release of the toggle bars in the correct sequence by the messengers (Fig. 2). This depends not only on the second trigger being offset far enough to obviate any danger of its being struck by the first messenger, but also on the second messenger (cupping the first) being large enough in diameter and long enough to receive proper guidance by the towing cable. Experience has also shown that unless the messengers are bored somewhat oversize the vibration of the cable may impede their progress downward through the water.

---

[1] Contribution No. 174 of the Woods Hole Oceanographic Institution.

[2] Following Iselin (1933) the term "Gulf Stream" is used to include not only the band of warmest surface water or that wherein the northeastward current is most pronounced, but the whole body of water, extending down to 2,000 meters, across which the isotherms and isohalines dip steeply in the inshore-offshore direction.

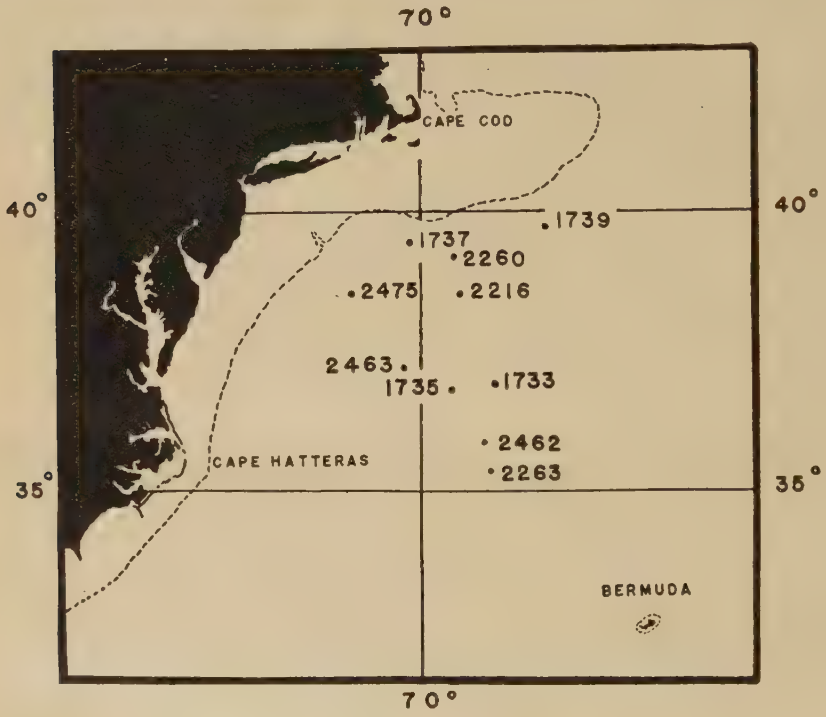


Fig. 1. Location of stations.

The releasing device and messengers are adapted for use in series and four nets were used, simultaneously, on the one cable.

Since there is no way of determining, from the condition of the nets themselves, on their arrival at the surface, whether they were open the full period of the tow, but only whether the proper bridles were released, we must turn to the consistency of the results for evidence in this respect. It will be seen in Table I that we usually found more than one rich level in the upper part of the water column, followed by two or more poor catches in mid-depths, with two or three somewhat more productive hauls still deeper. It is very unlikely that nets would consistently fish well at the shoaler levels, fail at the mid-levels, but work well still deeper down. Nor is it conceivable that hauls from the same depths would fail every time at the same depths at different stations in different years. Stations 2216, 2260, and 2462 are particularly significant in this respect, for they show a marked similarity in vertical distribution (Table I). These similarities may be considered strong evidence for the adequacy of our technique since the first two stations were made two months apart, and the third a year later, all in the same general water mass.

Table I *

Catches in cubic centimeters, calculated per 2 hours towing with a 2-meter net

Sta....	1735	1737	1739	2216	2260	2263	2462	2463	2475	Average
Date...	7/28/33	7/30/33	8/12/33	6/11/34	8/19/34	8/23/34	7/27/35	7/31/35	8/31/35	
Lat....	36°50′N	39°29′N	39°42′N	38°26′N	39°12′N	35°17′N	35°50′N	37°21′N	38°46′N	
Long...	69°16′W	70°14′W	67°04′W	69°05′W	69°13′W	67°28′W	68°39′W	70°26′W	71°38′W	
200M.	105	300	250	200	93	33	105	375	521	221
400...	50	280	255	18	105	84	33	200	122	105
600...	55	280	345	70	210	23	48	134	181	150
800...	50	225	270	500	510	78	64	57	115	207
1000...	33	125	150	45	10	75	42	54	148	77
1200...	16	20	23	20	5	75	18	51	140	41
1400...	37	57	27	55	90	35	4	35	8	39
1600...	60	93	30	300	25	25	35	24	29	69
1800...	80	125	45	70	3	8	10	9	0	31
2000...	100	160	60	0	40	15	20	11	0	45
2200...			105	10	60	38	17	5		
2400...			151	12		32	62	4		
2600...			185	4		6		7		
2800...			220	2		4		4		
3000...			256	13		0		2		
3200...			0			2				

* Positions and dates given are for the starting points of tows.

Another proof of the accuracy of the method is found in the fact that in a great majority of the cases where hauls were repeated at the same level at the same station, the variation in the amount of material caught was less than 30 per cent and often less than 10 per cent. In short, it seems that the methods employed were sufficiently reliable to yield consistent results.

The stated depths are as calculated from the length of wire outboard and its angle with no allowance for catenary. Failure to take account of the latter no doubt introduces an error, the magnitude of which is assumed to be not greater than ± 100 meters. In any case, it should be approximately the same for all hauls at a given level as care was taken to maintain a constant wire angle and control of the speed of the ship. The average speed of towing was close to two miles per hour in all cases.

The problem at hand being the difference in the productivity of the different levels of the sea, a volumetric system of analysis seems as significant as any other yet devised.

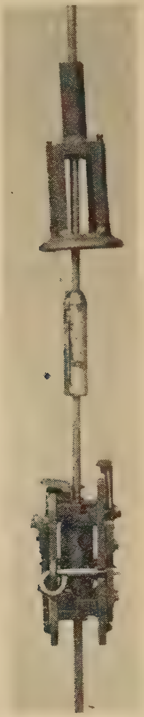


Fig. 2. Releasing device and messengers.

The total volumes of all the catches were first measured by the displacement method (Leavitt, 1935, p. 120), the volumes of the following groups then measured separately: fish, copepods, decapods, euphausiïds, chætognaths, cœlenterates, salps, and "residue."

Since the duration of the tows at different stations varied between one and two hours and since a few of the early tows were made with nets of different sizes, all volumes have been reduced to the common standard of two hours towing with a 2-meter net.

In addition to the volumetric measurements, the euphausiïds were all identified and counted. In some cases, when great numbers were caught, it was necessary to use a sampling method for counting closely allied species (Leavitt, 1935, p. 125). Some other groups[3] which were of particular interest in certain of the hauls have also been identified

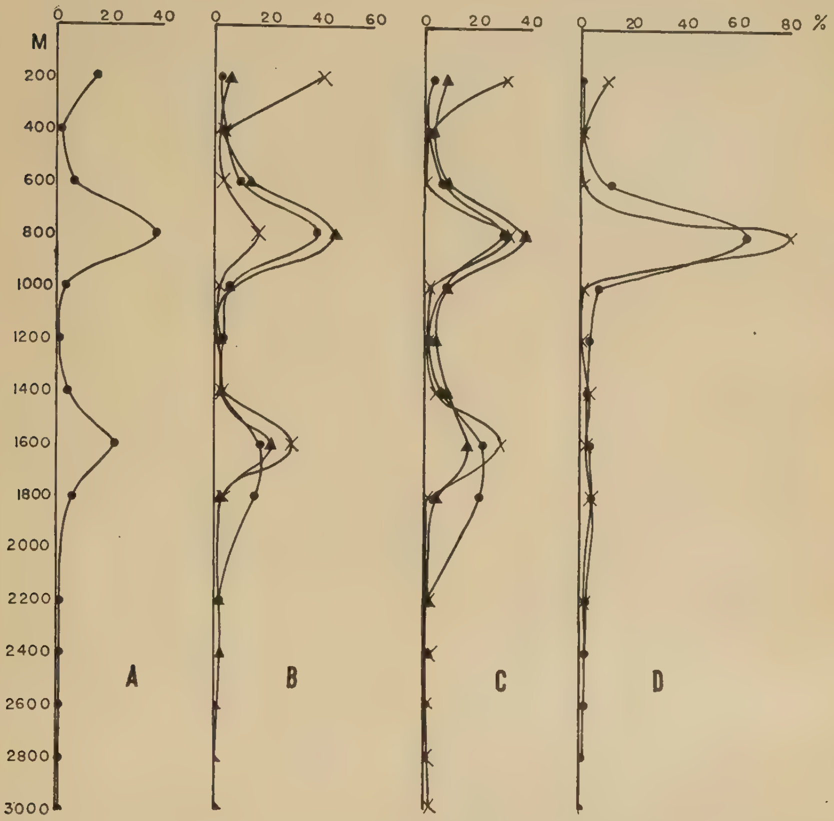


FIG. 3. Percentages of catch, at different levels at Station 2216. *A.* Percentage of total catch. *B.* Percentage of fish (●), copepods (▲), and euphausiids (×). *C.* Percentage of decapods (●), chætognaths (▲), and salps (×). *D.* Percentage of cœlenterates (●), and "residue" (×).

and counted, either in aliquot samples or in the entire catch, when the latter was small.

RESULTS

The most obvious feature of vertical distribution, illustrated by the foregoing tabulation, is that in spite of wide differences in detail from station to station, all stations agree in showing a peak of abundance at some level shoaler than 1,000 meters. And the validity of this generalization is corroborated by the fact that, on the whole, the percentual distribution of the catches of the different groups at a given station, parallels that for the total catch there, as illustrated by Fig. 3 (derived from Table I).

---

[3] Drs. M. Sears, H. B. Bigelow, and F. Chace have assisted with the identification of copepods, cœlenterates, and decapods.

In some instances, it is true, the curves for single groups show seemingly large peaks at depths where none appear on the curves for the total volumes. This is accounted for by the fact that the percentage of a single group at one level may be great when the importance of that group in the total community is negligible. Such instances are, however, exceptional.

TABLE II

Station No.	Percentage taken above 700 meters per cent	Depth at deepest haul meters
1735	58	2,000
1737	93	2,000
	Percentage taken above 800 meters per cent	
1739 *	—	3,200
2216	60	3,000
2260	80	2,200
2263	40	3,200
2462	55	2,400
2463	68	3,000
2475	85	2,000

* At Station 1739, the only station at which there were a great many salpæ, over 94 per cent of the plankton caught was taken between 800 meters and the surface. If we subtract the volume of salpæ which constituted over 80 per cent of the total catch in four out of the thirteen hauls, approximately 74 per cent of the catch was taken between 800 meters and the surface, 26 per cent in depths greater than 800 meters.

The prevailing richness of the upper 800 meters, contrasted with the barrenness of the underlying stratum, is further emphasized by the following tabulation of the percentage of the total catch that was taken in the upper part of the water column (Table II).

It seems sufficiently established from Table II that from 40 per cent to over 90 per cent of the animals (by volume) were living in depths less than 800 meters, which is not surprising in view of the works of many early investigators. Within this upper zone the curves for individual stations differ widely, one from another, in the presence or absence of pronounced peaks (of abundance), and in the depths at which such peaks occur (Stations 2216, 2260, 2463, 2475, and to a lesser extent at 1739). Such peaks, in the upper levels, which include the photic zone, may reflect the recognized vertical migration of some surface animals, the gregarious habits of others, as well as the fact that the phytoplankton is confined to this layer, so that one would therefore expect a more erratic vertical distribution of the quantity of plankton there.

Strongly contrasting with the abundant peopling above, is the fact that at every station, the water contained much smaller volumes of plankton either at 1,200 meters, at 1,400 meters, or at 1,800 meters, than at any shoaler level, appearing on the individual curves as distinct minima. However, the comparatively barren zone still contained a small amount of plankton, composed largely of dead and decomposing corpses in many instances, but in several cases (particularly Stations 1735, 2216, 2260, and 2462), there were living copepods, chætognaths, decapods, and an occasional amphipod and cœlenterate present, though in very small numbers.

Perhaps the most significant results of our exploration is that in 8 out of 9 cases, at least one level still deeper down proved considerably richer again, in plankton, either as a distinct maximum (Station 2216), as two such maxima (Stations 2260, 2465), or as a progressive increase in abundance, extending downward through a stratum several hundred meters in thickness (Stations 1735, 1737, 1739). In the extreme case (Station 2462), the secondary maximum at 2,400 meters was in fact some sixteen times as rich as the overlying minumum; in another case (Station 2216), the tow was fifteen times as productive at 1,600 meters as at 1,200 meters.

Corresponding to this, the average catch, for all stations combined, was about 1.5 to 1.8 times as large at 1,600 meters as at 1,200–1,400 meters. And while averages for greater depths perhaps are not significant, because only four of the stations were worked deeper than 2,400 meters, calculation of what percentage of the catch for the entire column was made at different depths shows a similar relationship (Fig. 4), followed by decrease from 1,600 meters to 2,000. Deeper than this, the average percentages were consistently insignificant down to the greatest depths fished, except at one station (1739) where the stratum between 2,400 and 3,000 meters rivalled the upper 800 meters in richness. Even in that case, however, the deepest haul (3,200 meters) yielded nothing at all, although the net appeared to have fished properly. At two other stations (2263, 2463), also depths greater than 2,400 meters were practically barren, and conditions at Station

2475 show that, on occasion, this may apply at as small a depth as 1,800–2,000 meters (for details, see Table I, p. 378).

It is also significant—as bearing on its origin—that in every case the existence of a comparatively rich stratum at great depths, reflects, not only the relative volumetric abundance of the community as a whole, but also that of several individual groups of animals, as typified by the recorded volumes of fish, copepods, euphausiïds, decapods, chætognaths, cœlenterates, salps, and "residue" at Station 2216 (Fig. 3). That these maxima represent widely diversified communities is further

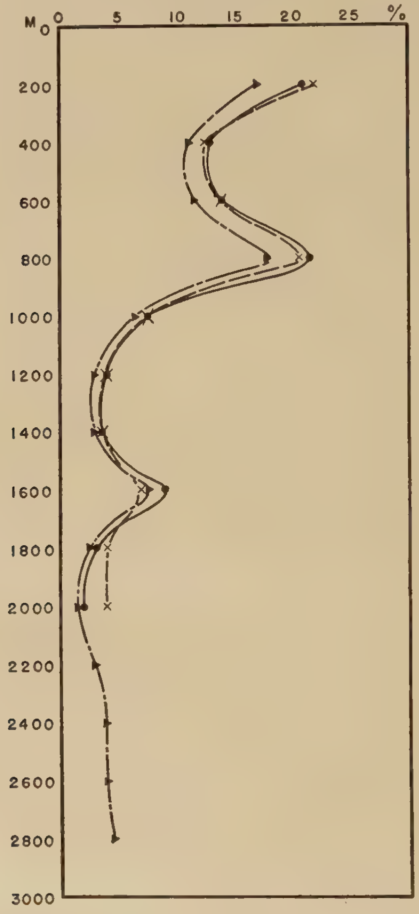


FIG. 4. Percentages of total catch to different levels based on data in Table I. ●, percentage at nine stations to 2,000 meters. ×, percentage at four stations to 2,000 meters. ▼, percentage at four stations to 2,800 meters.

proven by the large number of species of copepods and decapods represented in hauls at the depths in question, at representative stations, as follows:

Station 1735, 2,000 meters, copepods, immature *Metridia* sp., 75 per cent of sample, also *Metridia longa, Rhincalanus cornutus, Rhincalanus nasutus, Paraeuchæta norvegica, Paraeuchæta barbata.*

Station 1737, 2,000 meters, immature *Metridia* sp., 24 per cent of sample, also the species listed above, and *Lucicutia grandis,* and decapods, *Eucopia biunguiculata, Hymenodora* sp.

Station 1739, 2,800–3,000 meters, copepods, immature *Metridia* sp., 37 per cent of sample, also *Calanus* sp., *Candacia* sp., *Corycæus* sp., *Eucalanus* sp., *Euchæta* sp., *Euchirella* sp., *Gætanus* sp., *Lucicutia* sp., *Oithona* sp., *Oncæa* sp., *Phyllopus* sp., *Metridia lucens, Metridia princeps, Pleuromamma abdominalis, Pleuromamma gracilis, Pleuromamma robusta, Pleuromamma xiphias, Pseudochirella obtusa, Rhincalanus cornutus, Rhincalanus nasutus, Scaphocalanus* sp., *Scolecithrix danæ, Scottocalanus securifrons, Temora stylifera, Valdiviella insignis.*

Station 2216, 1,600 meters, copepods, immature *Paraeuchæta* sp., 51 per cent of sample, also, *Euchirella intermedia, Euchirella messinensis, Euchirella rostrata, Heterostylites longicornis, Metridia princeps, Paraeuchæta barbata, Paraeuchæta norvegica, Pleuromamma robusta, Pleuromamma xiphias, Pseudochirella notocantha, Rhincalanus cornutus, Rhincalanus nasutus;* decapods, *Acanthephyra purpurea, Ephyrina benedictæ, Eucopia* sp., *Gennadus* sp., *Hymenodora glacialis, Sergestes* sp., and mysids.

Station 2462, 2,400 meters, copepods, *Euchæta* sp., 20 per cent of sample, *Lucicutia grandis,* 11 per cent, *Paraeuchæta barbata,* 14 per cent, *Rhincalanus nasutus,* 17 per cent, also, *Euchæta marina, Gaidius* sp., *Megacalanus* sp., *Metridia princeps, Paraeuchæta norvegica, Pseudochirella paliata, Pseudochirella pustilifera, Rhincalanus cornutus;* decapods, 1 *Gnathophausia* sp., 1 *Parapasiphæ sulcatifrons;* cœlenterates, 1 *Halicreas papillosum,* 1 *Homeonema* sp., 6 *Periphylla hyacinthina.*

Station 2475, 1,600 meters, copepods, *Rhincalanus nasutus,* 30 per cent of total copepods (310), *Calanus* sp. (immature), and *Paraeuchæta norvegica,* together, 40 per cent; the remainder represented 15 other species, all of which have previously been found at similar depths.

Other hauls at the levels of the secondary maxima (Station 2260, 2,200 meters, Station 2263, 2,200 meters, Station 2462, 1,600 meters, Station 2463, 2,000 meters) similarly yielded from one to seven specimens each among the following cœlenterates and ctenophores, *Æginura grimaldii, Amphicaryon acaule, Atolla bairdii, Beræ* sp., *Chuniphyes multidentata, Halicreas minimum, Hippopodius hippopus, Homeonema* sp., *Pantachogon rubrum, Periphylla hyacinthina,* and *Rhopalonema funerarium.*

VERTICAL DISTRIBUTION OF EUPHAUSIÏDS

The euphausiïds have been chosen as a representative group of animals for numerical analysis for the reason that they are holoplanktonic and are worldwide in their distribution as a group, that they extend their vertical distribution to all depths of the ocean, that the species are not so numerous but what one may readily become familiar with them, and that little is known of their quantitative vertical distribution outside the continental shelves.

Evidence that our hauls contained a representation of species sufficiently broad to be accepted as typical of mid-latitudes, on the high seas, is that they yielded all but one of the 27 species recorded by Tattersall (1926) from the collections made in 1914 by the U. S. C. G. Steamer "Bache" in waters adjacent to and south of the positions where the present collections were made. And this one (*Thysanoessa microphthalma*) appears to be confined to lower latitudes of the Atlantic and Pacific, north and south (Hansen, 1915). On the other hand, our collection contains eleven which the "Bache" failed to find, namely, *Thysanopoda orientalis, T. obtusifrons, T. acutifrons, Euphausia pseudogibba, Thysanoessa parva, T. inermis, T. longicaudata, Nematoscelis atlantica, Stylocheiron affine, S. insulare.*[4]

Similarly, the present collections contain all the species reported by Hansen (1912) from the same general region, besides twelve others which he does not record there, although several of these are known to be widely distributed in the western Atlantic, and have been taken not far away; namely, *Thysanopoda tricuspidata, T. pectinata, T. obtusifrons, Euphausia pseudogibba, Nematobrachion flexipes, N. boöpis, Stylocheiron longicorne, S. abbreviatum, S. affine, S. maximum, S. suhmii,* and *S. insulare.* Seven of these are recorded from farther south by Tattersall (1926). Again, we find, in the "Atlantis" collection, all but two of the species reported by Ruud (1936) from southwest of Ireland, from Cadiz Bay, and from the Mediterranean. And one of these (*T. microphthalma*) had already been reported from the western North Atlantic by Tattersall (1926), while the other (*Nyctiphanes couchii*) is a coastal species, so far known only in the Mediterranean and the eastern Atlantic.

We may conclude from the foregoing comparisons that we are dealing with a good representation of the total euphausiïd fauna of the

---

[4] *Meganyctiphanes norvegica* was also taken in several tows at stations 1739 from unkown depths.

TABLE III

Total numbers of specimens of euphausiids caught at different depths, at Stations 2216, 2260, 2263, 2462, 2463, and 2475 combined.

Depth	200	400	600	800	1,000	1,200	1,400	1,600	1,800	2,000	2,200	2,400	2,600	2,800	3,000
Number of hauls	7	8	8	7	6	6	6	7	5	6	6	4	3	3	2
Meganyctiphanes norvegica	37	258	3												
Thysanopoda orientales			8	14	1	1			1			1			
Thysanopoda tricuspidata															
Thysanopoda pectinata		3	1	3											
Thysanopoda acutifrons				1											
Thysanopoda æqualis	8		1	61				1							
Thysanopoda monocantha		14	2	3											
Thysanopoda cornuta			1												
Thysanopoda obtusifrons											3				
Euphausia tenera	1	92	110	97				11			16				
Euphausia americana	2	10		61											
Euphausia krohnii	3,068	49	4	4	3	3					1				
Euphausia hemigibba	4	753	243	24	12			4			10				
Euphausia pseudogibba		17		69				12			14				
Euphausia gibboides	21														
Euphausia mutica			52												
Euphausia brevis	48			24				4				5			4
Thysanoessa gregaria	2,439	77	230		1	16									
Thysanoessa parva		2	262	1,941	466	699	926	2,804	91	88	1,540	480	1	1	4
Thysanoessa inermis		2													
Thysanoessa longicaudata	3	1,504	222	201	328		94								
Nematoscelis megalops	11,670	29,694	2,043	7		1		466			8				
Nematoscelis microps	82	231	92	62	24	307		23		2	7	2			

TABLE III (*Continued*)

Depth	200	400	600	800	1,000	1,200	1,400	1,600	1,800	2,000	2,200	2,400	2,600	2,800	3,000
Number of hauls	7	8	8	7	6	6	6	7	5	6	6	4	3	3	2
Nematoscelis atlantica			98	105											
Nematoscelis tenella	8	6	14	12											
Nematobrachion flexipes	9	12	18												
Nematobrachion sexspinosus		1	1												
Nematobrachion boöpis		3	3			6									
Stylocheiron carinatum	8	28													
Stylocheiron longicorne	555	347	14	5	2	1			1		8				
Stylocheiron elongatum															
Stylocheiron abbreviatum															
Stylocheiron affine	4							1							
Stylocheiron maximum		2	5	8											
Stylocheiron suhmii															
Stylocheiron insulare	19							2							
Bentheuphausia ambylops		1		4	5	7	3	3		2	2				
Thysanoessa sp.	2	1							3						
Thysanoessa sp. young								3							
Euphausia sp. young	4							3							
Nematoscelis sp. young	14														
Stylocheiron sp.	5	1													
Euphausia sp.		36		1		1			2	4					
Thysanopoda young				4											
Young Euphausids	89	4		2											
Nematobrachion sp.				1							6				
Nematoscelis sp.					1										

western Atlantic basin, especially in the fact that the list of species is a combination of northern with southern forms, to be explained by the latitudes at which the collections were made.

Earlier data (Leavitt, 1935, Tables II–V), and Table III of this paper show that the numbers of euphausiids taken was much smaller at great depths than at the shallower levels, for 86 per cent of the 76,790 specimens identified and counted were from tows between 800 meters and the surface, whereas only 14 per cent were from depths greater than 800 meters. These percentages are similar to those of the total volumes (p. 381).

Many of the euphausiids are notably gregarious animals and this fact coupled with vertical diurnal migrations may account for the unevenness of their occurrence in the upper layers.

In order to determine the relative importance of euphausiids as a whole in the community, the numbers of euphausiids per 50 cc. of plankton caught at each depth was estimated at four stations (Leavitt, 1935). While the numbers of euphausiids, like the quantities of plankton, increased on the average below 1,200 meters, the importance of this group in the total animal community decreased down to the deepest layer sampled, the number of euphausiids per 50 cc. of plankton being only about one-fourth as great at depths greater than 800 meters than in the upper layers.

There are few reliable data on the depth at which different species of euphausiids are to be found and Ruud (1936) regards temperature as one of the most important limiting factors of the distribution of the different species of this group. Since all but nine of the species recorded by him belong to groups most abundant between 200 meters and the surface, and since our shallowest hauls were at 200 meters, the data can hardly be compared with his. But among the nine species that he regarded as deep-sea forms, it is interesting to note that *T. gregaria* (regarded by Zimmer (1914) as bipolar) occurred abundantly at a depth of 2,000 meters at Station 1735, and *T. parva,* which did not occur in Ruud's material, may be regarded as even more persistently bathypelagic, on the basis of the present catches.

The decrease in numbers of euphausiids with increasing depth is accompanied by a corresponding decrease in the specific diversity of the group, for Table III shows only 18 species out of the total of 37, as occurring at all, below 800 meters and most of them in such small numbers (sometimes a single specimen) that only *Bentheuphausia amblyops* and *Thysanoessa parva* can be regarded as truly bathypelagic in these waters.

Thus, it seems sufficiently established, at least for this part of the ocean, and time of year, that euphausiids as a group reach their highest development in the upper 800 meters.

In the main, however, it is obvious, in common with Tattersall's (1926) experience, that the species in question show a deeper vertical range in the area investigated than in the eastern Atlantic and Mediterranean areas surveyed by the "Thor" (Ruud, 1936).

Discussion

Vertical Distribution

The precipitous variation in the abundance of a species in a given area has often been remarked. Michael's (1911, 1913) and Hardy's (1936) statistics as to the variation in numbers of chætognaths and other animals caught in a single place with successive hauls, and in closely proximate places, emphasize the fact that generalizations concerning distribution are extremely hazardous. Hence, we must realize the dynamic character of the plankton, and that attempts at a hard and fast terminology of the regions of vertical distribution are futile. It is only by continued observations over a period of time with a great many hauls that general ideas of distribution can be arrived at. Single hauls at separate localities can only be regarded as proof that what was caught was present at that particular time and place where the tow was made.

Nevertheless, it seems established by our investigations that in the region examined the abundant surface fauna decreases in quantity to a comparatively barren zone at a depth somewhere between 1,200 and 1,800 meters and that—in this particular region, at least—this minimum is followed by a subsequent increase in volume, at some greater depth.

Broadly considered, this is in line with previous knowledge, based largely on the work of Chun (1888, 1895), Alexander Agassiz (1888, 1892, 1902), Haeckel (1890), and Fowler (1898, 1904) that while pelagic animals live at all depths in the sea, with wide variety of species even at great depths, a much larger quantity occurs in the upper 800 meters or so than in deeper water.

Fowler's (1904) data on plankton from the Bay of Biscay is of particular interest in the present connection as the first detailed study of vertical distribution down to great depths in a restricted area, based on closing net hauls.

Subsequent investigators, including Esterly (1912), Murray and Hjort (1912), Michael (1913), Jespersen (1915, 1923, 1935), Hardy and Gunther (1936), Leloup and Hentschel (1935), Thiel (1935), Ramner (1935), and Bigelow and Sears (1937), have also recorded vertical variations in quantity for siphonophores, medusæ, copepods, fish, chætognaths, corycæens, and plankton as a whole. In none of these cases are the data of a sort to show whether or not there was any consistent increase in the volumes of plankton with increasing depth below the 1,200–1,800-meter level.

The plankton-poor layer encountered by "Atlantis" somewhere between 1,200 and 1,800 meters is presaged by A. Agassiz (1888) and others. The rich streak at greater depths, however, was unexpected, and the animals found at these greater depths are holoplanktonic, not benthonic, as illustrated by the assemblage collected at Station 1739 from a depth of 3,200 meters, where the total depth was 3,674 meters. In fact, there was no indication of the presence of benthonic animals, in any of our hauls, nor, in fact, would such have been expected for even the deepest tows were still far above the bottom.

In view of the changes in the physical and chemical characteristics of water with increasing depths, it is interesting, in the first instance, to correlate the volumetric distribution, vertically, of the plankton of the open sea with the density, salinity, and temperature at different levels in the slope water and in the Gulf Stream beyond.

Typical graphs (Fig. 5) for temperature, salinity, and density for the waters in which these investigations were carried on show no correlation between any of these environmental factors, and the depth distribution of the animals. Thus, the temperatures at all depths are well within the range in which we find plankton thriving at other times and places. The salinity variations are too minute for us to suppose that they have any appreciable effect on the plankton in these waters. Again, we find the same animals living throughout wider ranges of salinity than are presented here. The density does not show any indication of layering such as might account for an accumulation of material at any particular level between the surface and the bottom. In the present case, there is no apparent correlation between quantities of plankton, and either oxygen or light. Neither do any of these characters of the water show fluctuations below a depth of 800 meters corresponding to the existence of the plankton minimum at 1,200–1,800 meters, or to the subsequent increases in the volume of plankton at some greater depth.

The minimum oxygen in cubic centimeters per liter does not fall below 60 per cent saturation or about 3.5 cc. per liter in any of the water which was fished (Seiwell, 1934). And comparison between data for oxygen and numbers of animals caught at many of the "Meteor" stations as reported by Wattenberg (1935), Spiess (1932), and Hentschel (1932) shows that an abundance was caught in water where the oxygen content was much lower than at any level in the waters with which the present investigations are concerned. We must, therefore, conclude that there is ample oxygen to support planktonic communities at all depths there.

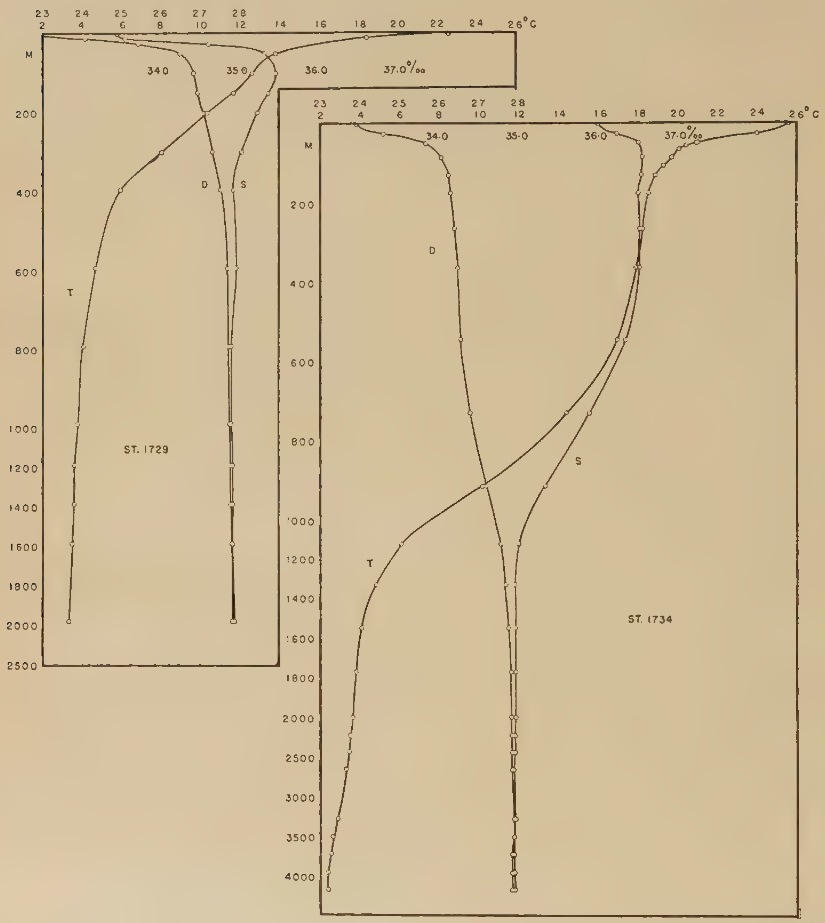


Fig. 5. Temperature, salinity, and density at "Atlantis" Station 1729, typical of slope water between the Continental Shelf and Gulf Stream and at Station 1734, typical of Sargasso Sea water east of the Gulf Stream, in the area of these investigations. *T*, temperature in °C. *S*, salinity in parts per mille. *D*, density (specific gravity minus one, times one thousand).

Among other possible causes for such vertical variations in abundance of plankton as do occur in deep water, the following possibilities come to mind:

(*a*) Dead and decomposing animals sifting down from the surface are sometimes caught in deep hauls. This happens oftenest with *Iasis zonaria,* the firmest bodied salp, pieces of which are found among the other dead and decomposing animal matter in deep hauls. Other salpidæ, also, contain cellulose which might be expected to disintegrate slowly.

(*b*) An occasional large medusa, *Periphylla hyacinthina* or *Atolla bairdii,* or some large deep-sea decapod, may rarely be responsible for a relatively voluminous catch at a great depth.

(*c*) A well developed bathypelagic fauna may—for some undetermined reason—find some particular deep levels more suitable as an abode than the levels above or below. The general identity of the animals taken in our tows shows this not to be the case.

(*d*) Sinking water masses from more moderate depths, in somewhat higher latitudes may bring their planktonic communities with them and so be responsible for richer strata below poorer, farther south. This last seems the most probable explanation for such a distribution in the present case, because species of decapods, copepods, cœlenterates, and euphausiids occurring at moderate depths somewhat farther north have been prominent in the catches where total volumes have revealed the existence of secondary maxima, deep down. This, for example, applies to *Calanus finmarchicus, Metridia longa, Paraeuchæta norvegica, Rhincalanus nasutus, Rhincalanus cornutus, Pleuromamma abdominalis, Pleuromamma gracilis, Pleuromamma robusta, Pleuromamma xiphias,* among the copepods, several species of Gennadus, among the decapods, and *Thysanoessa gregaria,* among the euphausiids.

It is likely that the animals belonging in this category are able to maintain themselves even in the deepest water layers for a considerable length of time, and that great depths may constitute the outskirts of the areas which they regularly populate. Lack of light may not harm them. Dr. C. B. Wilson has informed me that his examination of copepod material brought back from the Byrd Antarctic Expedition showed that many (including larval forms) were taken from under the ice, where it was totally dark, and far from open water. The "Terra Nova" Expedition also obtained many thousands of specimens under the ice (Farran, 1929). In short, communities may maintain themselves for a long time after sinking. We may have a biological loss, akin to that of the animals and plants that drift north and to their deaths in the surface waters of the Gulf Stream every summer.

While examination of vertical distribution was our primary objective, one phase of the horizontal picture deserves at least passing mention, namely the poverty of the catches in the Sargasso Sea water and in the

Gulf Stream, as defined on p. 376, contrasted with the slope water, the average catch (to 2,000 meters) being only 415 cc. in the first of these regions, 586 cc. in the second, contrasted with 1,283 cc. in the third. This regional gradient is of the same order as reported by Jespersen (1923, p. 8, Fig. 23) for average volumes for the upper 600 meters farther to the south, and is also in line with the prevailing poverty of the Sargasso Sea region, subsequently demonstrated by him (Jespersen, 1935, Figs. 27, 28).

BIBLIOGRAPHY

Agassiz, A., 1888. Three cruises of the "Blake." *Bull. Mus. Compar. Zoöl.,* **14**: 1; **15**: 1.

Agassiz, A., 1892. General sketch of the expedition of the "Albatross," from February to May, 1891. *Bull. Mus. Compar. Zoöl.,* **23** (No. 1) : 1.

Agassiz, A., 1902. Preliminary report and list of stations ("Albatross" 1899 and 1900). *Mem. Mus. Compar. Zoöl.,* **26**: No. 1, p. 1.

Bigelow, H. B., and Mary Sears, 1937. Siphonophoræ. *Rept. Danish Oceanog. Exped., 1908–1910 to the Mediterranean and Adjacent Seas.* Vol. 2, Pt. 2, p. 1.

Chun, C., 1888. Die pelagische Thierwelt in grösseren Meerestiefen und ihre Beziehungen zu der Oberflächenfauna. *Bibliotheca Zoologica,* **1** (Heft 1) : 1.

Chun, C., 1895. Biologische Studien über pelagische Organismen. *Bibliotheca Zoologica.* Heft 19, Lieferung 1, p. 1.

Esterly, C. O., 1912. The occurrence and vertical distribution of the Copepoda of the San Diego region. *Univ. Calif. Publ. Zoöl.,* **9** (No. 6) : 253–340.

Farran, G. P., 1929. British Antarctic ("Terra Nova") Expedition, 1910. Natural History Repts. Zoölogy, Vol. VIII, Crustacea, No. 3, Part X, Copepoda, pp. 203–306.

Fowler, G. H., 1898. Contributions to our knowledge of the plankton of the Faerœ Channel. No. VI. *Proc. Zoöl. Soc. London,* pp. 567–585.

Fowler, G. H., 1904. Biscayan plankton collected during a cruise of H. M. S. "Research," 1900. *Trans. Linn. Soc., London,* **10** (Pt. I) : 1.

Haeckel, Ernst, 1890. Plankton Studien. *Jenaische Zeitschrift,* XXV, and translated by G. W. Field as Appendix 6 to the *Report of the Commissioner for 1889, 1891, U. S. Com. Fish and Fisheries, Washington, 1893,* pp. 565–641.

Hansen, H. J., 1912. The Schizopoda. Reports . . . U. S. Fish Com. . . . "Albatross." *Mem. Mus. Compar. Zoöl.,* **35**: 175–296.

Hansen, H. J., 1915. The Crustacea Euphausiacea of the United States National Museum. *Proc. U. S. Nat. Mus.,* **48**: 59–114.

Hardy, A. C., 1936. Observations on the uneven distribution of oceanic plankton. *Discovery Reports,* **11**: 511–538.

Hardy, A. C., and E. R. Gunther, 1935. The plankton of the South Georgia whaling grounds and adjacent waters, 1926–1927. *Discovery Reports,* **11**: 1–456.

Hentschel, E., 1932. Die biologischen Methoden und das biologische Beobachtungsmaterial der "Meteor" Expedition. *Wiss. Ergeb. Deutschen Atlant. Exped. "Meteor," 1925–1927.* Vols. 10 and 11. Berlin and Leipzig.

Iselin, C. O'D., 1933. The development of our conception of the Gulf Streams system. *Trans. Am. Geophys. Union Fourteenth Annual Meeting,* pp. 226–231.

JESPERSEN, P., 1915. Sternoptychidæ (Argyropelecus and Sternoptyx). *Rept. Danish Oceanog. Exped. 1908–1910 to the Mediterranean and Adjacent Seas,* No. 3, Vol. II (Biol.), A. 2., pp. 1–41.

JESPERSEN, P., 1923. On the quantity of macroplancton in the Mediterranean and the Atlantic. *Rept. Danish Oceanog. Exped. 1908–1910,* No. 7, Vol. III, Misc. papers, Pt. 3, pp. 1–17.

JESPERSEN, P., 1935. Quantitive investigations on the distribution of macroplancton in different oceanic regions. *Dana Report,* No. 7, p. 1.

LEAVITT, B. B., 1935. A quantitative study of the vertical distribution of the larger zoöplankton in deep water. *Biol. Bull.,* **68**: 115–130.

LELOUP, E., AND HENTSCHEL, E., 1935. Die Verbreitung der calycophoren Siphonophoren im Südatalantischen Ozean. *Wiss. Ergeb. Deutschen Atlant. Exped. "Meteor," 1925–1927,* Vol. 12, Pt. 2, pp. 1–31.

MICHAEL, E. L., 1911. Classification and vertical distribution of the Chætognatha of the San Diego region. *Univ. of Calif. Publ. Zoöl.,* **8**: 21–186.

MICHAEL, E. L., 1913. Vertical distribution of the Chætognatha of the San Diego region in relation to the question of isolation vs. coincidence. *Am. Nat.,* **47**: 17–49.

MURRAY, J., AND J. HJORT, 1912. The Depths of the Ocean. MacMillan and Co. Ltd., London.

RAMNER, W., 1935. Die Cladoceren der "Meteor" Expedition. *Wiss. Ergeb. Deutschen Atlant. Exped. Meteor, 1925–1927,* Vol. 12, Pt. I, pp. 111–121.

RUUD, J. T., 1936. Euphausiacea. *Rept. Danish Oceanog. Exped. 1908–1910 to the Mediterranean and Adjacent Seas,* Vol. II, D. 6, pp. 1–86.

SEIWELL, H. R., 1934. The distribution of oxygen in the western basin of the North Atlantic. *Papers in Physical Oceanography and Meteorology published by Massachusetts Institute of Technology and W. H. O. I.,* Vol. III, No. 1, pp. 1–86.

SPIESS, F., 1932. Das Forschungsschiff und seine Reise. *Wiss. Ergeb. Deutschen Atlant. Exped. "Meteor" 1925–1927,* Vol. I, pp. 1–413.

TATTERSALL, W. M., 1926. Crustaceans of the Orders Euphausiacea and Mysidacea from the western Atlantic. *Proc. U. S. Nat. Mus.,* Vol. 69, Art. 8, pp. 1–31.

THIEL, M. E., 1935. Die Besiedlung des Südatlantischen Ozeans mit Hydromedusen. *Wiss. Ergeb. Deutschen Atlant. Exped. "Meteor," 1925–1927,* Vol. 12, Pt. 2, pp. 32–100.

WATTENBERG, H., 1935. Das chemische Beobachtungsmaterial und seine Gewinnung. *Wiss. Ergeb. Deutschen Atlant. Exped. "Meteor," 1925–1927,* Vol. 8, pp. 9–121.

ZIMMER, CARL, 1914. Die Schizopoden der Deutschen Südpolar-Exp. 1901–1903. *Deutsch. Südpol. Exped.,* Bd. 15. Zool. Bd. 7, pp. 377–446.

Contribution No. 175

Reprinted from THE JOURNAL OF PHYSICAL CHEMISTRY
Vol. 42, No. 9, December, 1938

THE SOLUBILITY OF NITROGEN AND ARGON IN SEA WATER[1]

NORRIS W. RAKESTRAW AND VICTOR M. EMMEL

Woods Hole Oceanographic Institution, Woods Hole, Massachusetts

Received April 30, 1938

INTRODUCTION

We recently described a method for the determination of dissolved nitrogen in sea water (4), in which the air is removed from the water sample *in vacuo* and the oxygen, nitrogen, and inert gas residue are measured separately. In making such determinations on actual sea water it is often necessary to compare the values obtained with the equilibrium solubility of nitrogen from the atmosphere. The only figures available for such comparison are those obtained by Fox (2, 3), which have never been seriously questioned. Using these for comparison, however, our analyses consistently indicated an unsaturated condition of water from nearly all sources, with respect to gaseous nitrogen. Believing this to be unlikely, and convinced of the accuracy of our own method, we undertook a redetermination of the solubility of nitrogen in sea water of different temperatures and chlorine contents, within the range ordinarily encountered.

Fox's method consisted in the measurement of the volume of "atmospheric nitrogen" absorbed by a fixed volume of water from a known total volume of the gas. This requires a correction for the argon content of the "atmospheric nitrogen," which can probably be made with sufficient accuracy for our purpose, even though the absorption coefficient of argon in sea water is not well known. But in addition to this, considering the use to which these figures are to be put, it would seem preferable to let the water come into complete equilibrium with the actual atmosphere, rather than with nitrogen alone, and to determine the dissolved nitrogen directly, assuming a constant composition of the atmosphere. The results of such a procedure, described below, are slightly lower than those of Fox (corrected for argon), but are more consistent with the nitrogen content which we find in sea water in nature.

Examining Fox's method more closely, we suspected that his systems might have been supersaturated. He saturated the water by vigorous shaking for several minutes, followed by only a short period of standing, until the pressure became constant. We have found that on shaking sea

---

[1] Contribution No. 175 from the Woods Hole Oceanographic Institution.

TABLE 1

Experimental data

CHLORINE CONTENT	SAMPLE*	EQUILIBRIUM TEMPERATURE	EQUILIBRIUM PRESSURE	MEASURED VOLUME		EQUILIBRIUM SOLUBILITY AT 760 MM. ATMOSPHERIC PRESSURE IN MILLILITERS PER 1000 ML. OF WATER	
				Nitrogen	Residue	Nitrogen	"Argon"
grams per kilogram		*°C.*	*mm.*	*ml.*	*ml.*	*ml.*	*ml.*
16.03	A	2.11	766.3	1.434		14.22	
	A	7.08	758.7	1.262	0.0356	12.68	0.352
	B	7.08	758.7	1.262	0.0346		
	A	12.15	767.0	1.160	0.0317	11.53	0.312
	B	12.15	767.0	1.162	0.0312		
	A	18.03	765.5	1.038	0.0289	10.33	0.288
	B	18.03	765.5	1.041	0.0290		
	A	25.05	764.0	0.925	0.0242	9.19	0.240
	B	25.05	764.0	0.920	0.0244		
18.00	A	2.11	767.0	1.394		13.81	
	A	7.08	758.7	1.283	0.0339	12.40	0.341
	B	7.08	758.7	1.234	0.0340		
	A	12.15	766.3	1.134	0.0301	11.27	0.303
	B	12.15	766.3	1.134	0.0309		
	A	18.03	768.5	1.016	0.0274	10.05	0.270
	B	18.03	767.7	1.015	0.0272		
	A	25.05	763.2	0.903	0.0237	9.00	0.236
	B	25.05	762.5	0.903	0.0236		
19.99	A	2.11	767.0	1.363		13.50	
	A	7.08	758.7	1.203	0.0338	12.08	0.332
	B	7.08	758.7	1.201	0.0324		
	A	12.15	766.3			10.95	0.296
	B	12.15	766.3	1.103	0.0298		
	A	18.03	764.7	0.991	0.0271	9.89	0.266
	B	18.03	764.7	0.997	0.0265		
	A	25.05	762.5	0.880	0.0226	8.81	0.227
	B	25.05	762.5	0.886	0.0230		

* Sample A was saturated with air at a temperature above the equilibrium temperature; sample B at a temperature below.

water with air and allowing to stand until the air bubbles are no longer visible, the nitrogen content is regularly about 2 per cent higher than the equilibrium value at that temperature. It has long been known that the surface water of the sea may be supersaturated with air, from the abnormal solubility of fine bubbles of foam. We are of course in no position to urge that the difference between our solubility values and those of Fox is entirely due to this.

METHOD

Samples of natural sea water containing approximately 16, 18, and 20 g. of chlorine per kilogram were prepared by dilution from the highest concentration. Duplicate portions, of about 250 ml., were placed in citrate bottles, one of these warmed to about 30°C. and the other cooled to about 8°C., and both shaken for 30 min. to saturate them with air. They were then placed in a thermostat at 25°C. for 18 hr. to come to equilibrium, open to the air, with occasional but not too vigorous agitation. Both samples were then analyzed for nitrogen. The same was done at temperatures of 18°, 12°, 7°, and 2°C., the duplicate portions being always saturated at temperatures above and below the final equilibrium temperature, except in the case of the lowest one, in which this was not possible. It may safely be assumed that complete equilibrium was reached in this latter instance also, in view of the satisfactory agreement of the two samples at all other temperatures.

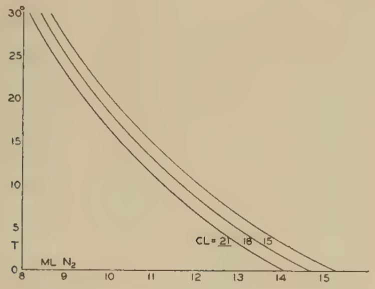


FIG. 1

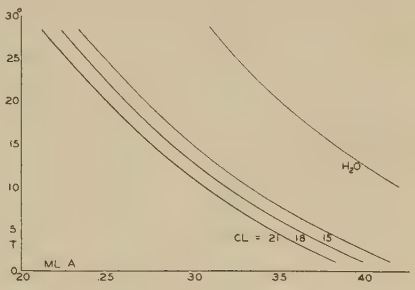


FIG. 2

FIG. 1. Solubility of nitrogen in sea water of different chlorine contents and temperatures. Solubility is expressed in milliliters of gas (at standard temperature and pressure) per liter of water, in equilibrium with air at 760 mm.

FIG. 2. Solubility of "argon" (total inert gas in atmosphere) in sea water of different chlorine contents and temperatures. Solubility is expressed in milliliters of gas (at standard temperature and pressure) per liter of water, in equilibrium with air at 760 mm. The curve for the solubility in pure water is taken from results of Estreicher (1).

The data are given in table 1. The barometric pressure is included, from which, in the last column, is calculated the equilibrium solubility in contact with a normal atmosphere of 760 mm.

It was thought worth while to measure the residual gas, after removal of carbon dioxide, oxygen, and nitrogen, and to include this as "argon," although these figures are of a distinctly lower order of accuracy. This crude fraction of inert gas will therefore be designated as argon, although obviously impure. These figures were obtained by measuring the pressure of the residual gas, when contained in the capillaries between the stopcocks

TABLE 2

Solubility of nitrogen in sea water

Expressed in milliliters (at standard temperature and pressure) per liter of water, from a normal atmosphere of 760 mm.

CHLORINE CONTENT	15	16	17	18	19	20	21
TEMPERATURE	SOLUBILITY						
°C.	*ml.*	*ml.*	*ml.*	*ml.*	*ml.*	*ml.*	*ml.*
0	15.22	15.02	14.82	14.61	14.40	14.21	14.01
1	14.81	14.61	14.42	14.23	14.04	13.85	13.66
2	14.43	14.24	14.06	13.88	13.69	13.51	13.33
3	14.07	13.89	13.72	13.54	13.36	13.19	13.01
4	13.73	13.56	13.40	13.24	13.06	12.89	12.72
5	13.43	13.26	13.10	12.94	12.78	12.62	12.45
6	13.14	12.98	12.82	12.67	12.51	12.35	12.19
7	12.88	12.72	12.56	12.41	12.26	12.10	11.95
8	12.62	12.47	12.32	12.17	12.02	11.87	11.71
9	12.38	12.23	12.08	11.94	11.79	11.64	11.49
10	12.15	12.00	11.86	11.71	11.56	11.42	11.27
11	11.92	11.78	11.63	11.49	11.34	11.20	11.06
12	11.69	11.56	11.42	11.28	11.13	10.99	10.85
13	11.47	11.34	11.21	11.07	10.93	10.79	10.65
14	11.25	11.13	10.99	10.86	10.73	10.59	10.45
15	11.04	10.92	10.79	10.66	10.53	10.39	10.26
16	10.83	10.72	10.59	10.47	10.34	10.21	10.08
17	10.63	10.52	10.40	10.28	10.15	10.03	9.91
18	10.44	10.33	10.21	10.10	9.98	9.86	9.74
19	10.26	10.15	10.03	9.92	9.81	9.69	9.58
20	10.08	9.98	9.87	9.76	9.65	9.54	9.43
21	9.91	9.82	9.71	9.61	9.50	9.39	9.28
22	9.75	9.66	9.56	9.46	9.35	9.24	9.14
23	9.60	9.51	9.41	9.31	9.20	9.10	9.00
24	9.45	9.36	9.26	9.16	9.06	8.96	8.86
25	9.30	9.21	9.11	9.02	8.92	8.82	8.73
26	9.16	9.07	8.97	8.88	8.79	8.60	8.60
27	9.02	8.94	8.84	8.75	8.66	8.56	8.47
28	8.89	8.84	8.72	8.62	8.53	8.44	8.35

1, 2, and 3 in the apparatus, shutting off the reservoir C, ordinarily used during the measurement of the oxygen and nitrogen.

Plotting the nitrogen and argon content against chlorine content, at different temperatures, gave a series of straight lines, from which points were taken for the construction of the curves in figures 1 and 2. From these curves tables 2 and 3 have been constructed.

TABLE 3

Solubility of "argon" in sea water

Expressed in milliliters (at standard temperature and pressure) per liter of water, from a normal atmosphere of 760 mm.

CHLORINE CONTENT............	15	16	17	18	19	20	21
TEMPERATURE	SOLUBILITY						
°C.	*ml.*	*ml.*	*ml.*	*ml.*	*ml.*	*ml.*	*ml.*
2	0.405	0.400	0.395	0.389	0.384	0.379	0.373
4	0.384	0.379	0.374	0.369	0.363	0.358	0.352
6	0.365	0.360	0.355	0.350	0.345	0.340	0.335
8	0.347	0.343	0.338	0.333	0.329	0.324	0.319
10	0.331	0.327	0.323	0.318	0.314	0.310	0.305
12	0.317	0.313	0.309	0.304	0.300	0.296	0.292
14	0.304	0.300	0.296	0.292	0.288	0.284	0.280
16	0.292	0.288	0.284	0.280	0.277	0.273	0.269
18	0.282	0.278	0.274	0.270	0.267	0.263	0.259
20	0.272	0.268	0.264	0.260	0.256	0.253	0.249
22	0.262	0.258	0.255	0.251	0.247	0.244	0.240
24	0.253	0.249	0.246	0.242	0.238	0.235	0.231
26	0.244	0.240	0.237	0.233	0.229	0.226	0.222
28	0.235	0.231	0.228	0.224	0.220	0.217	0.213

REFERENCES

(1) Estreicher, T.: Z. physik. Chem. **31**, 176 (1899).
(2) Fox, C. J. J.: Publ. de circonstance. Cons. perm. internat. #41 (1907).
(3) Fox, C. J. J.: Trans. Faraday Soc. **5**, 68 (1909).
(4) Rakestraw, N. W., and Emmel, V. M.: Ind. Eng. Chem., Anal. Ed. **9**, 344 (1937).

Contribution No. 176

Reprinted from Biological Bulletin, Vol. LXXIV, No. 3, 364–375, June, 1938
Printed in U. S. A.

EYES OF DEEP-SEA CRUSTACEANS

II. Sergestidae

J. H. WELSH AND F. A. CHACE, JR.

(From the Woods Hole Oceanographic Institution and the Biological Laboratories, Harvard University)

EYES OF DEEP-SEA CRUSTACEANS

II. Sergestidae

J. H. WELSH AND F. A. CHACE, JR.

(From the Woods Hole Oceanographic Institution[1] *and the Biological Laboratories, Harvard University)*

Introduction

In the first of this series of papers which dealt with the eyes of the Acanthephyridae (Welsh and Chace, 1937) it was shown that *Hymenodora glacialis,* a species of deep-sea prawn which normally lives at a level below the photic zone, has quite degenerate eyes, while related species which normally inhabit the photic zone have well-developed and obviously functional eyes. It was also shown that among the acanthephyrids of the photic zone those possessing photophores have larger eyes in proportion to body size than those which lack the means to produce light of their own. Since such correlations between the structural development of the eye, light intensity and the ability to produce light are of considerable interest from the standpoint of adaptation, the present study of the eyes of the Sergestidae was undertaken with these points in mind.

Much of the literature dealing with the eyes of deep-sea crustaceans was cited in the paper already referred to and since collecting methods were also discussed in this paper and one by Welsh, Chace and Nunnemacher (1937), it will be unnecessary to discuss these matters further.

We are greatly indebted to Dr. H. B. Bigelow for the privilege of continuing this work and to the Milton Fund Committee of Harvard University for a grant which cared for certain of the expenses of the investigation.

Characteristics and Distribution of the Sergestidae

The prawns which make up the family Sergestidae form a well-defined, aberrant group of the most primitive tribe of the Natantia, the Penaeidea. Since the species dealt with in this paper belong, in the main, to the genus *Sergestes* it is not necessary to dwell on the four remaining genera of the group.

---

[1] Contribution No. 176.

All of the species of *Sergestes* are slender-bodied animals with long, slender appendages (Fig. 1) and an integument that is never as firm as in most of the acanthephyrids. Despite their fragile appearance, most of the species retain their form and appendages fully as well as most other pelagic decapods when subjected to the usual handling. The last two pairs of thoracic legs are flattened and shorter than the other three pairs and fringed with long hairs. These, in conjunction with the long, well-developed pleopods suggest that the sergestids are among the fastest swimming of the pelagic Crustacea. Further indication that such is the case is provided by the fact that very few adult specimens and practically none of the mature individuals of the larger species were captured until the advent of the motor-driven vessel which was able to tow nets at a fairly rapid rate of speed. In collections now made with modern ships and apparatus, however, sergestids are very frequently encountered, and a number of the North Atlantic species are apparently reasonably abundant in the midwater area; possibly the commonest species in any one region is the luminous species, *Sergestes lucens* Hansen, from off Japan, of which 10 million pounds are said to be taken annually by commercial fisheries.

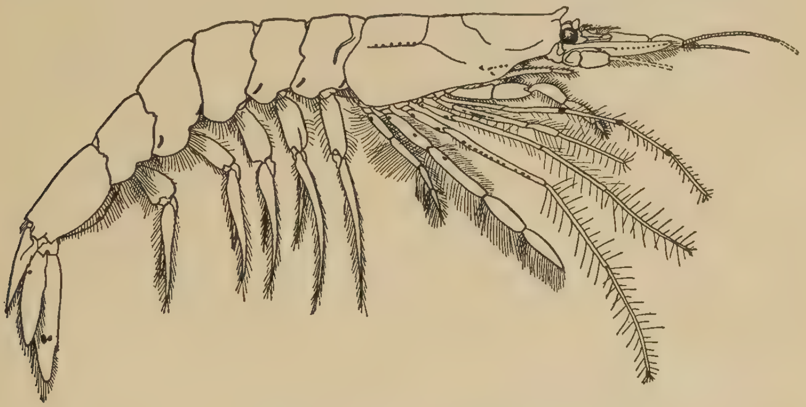


FIG. 1. *Sergestes grandis* Sund, female, showing certain of the features which characterize sergestids. Photophores, which are present only in certain species, are indicated by solid black spots.

The lack of adult individuals and the extremely long and complicated larval history of these animals were the chief obstacles in the path of the correct determination of species by the early carcinologists. Innumerable species have been described, a great many on larval forms, and it was not until the last few years that any idea of the number of valid species could be learned. It is estimated that there are between thirty and thirty-five species of *Sergestes,* and even now several comparisons, particularly between Atlantic and Pacific specimens, are necessary before the exact number of known forms can be ascertained.

Although they inhabit the general "black fish-red prawn" area, only two of the sixteen species known from the North Atlantic are distinctly red in color. The others range from a deep rose pink and a pattern of red spots to almost perfectly transparent forms in which the internal organs may be clearly seen.

In 1903 photophores or luminescent organs were observed for the first time in any species of the genus and since then they have been described in four other species. Recently organs which are probably photophores have been detected in three other Atlantic species. It is very probable that further study of fresh material will show that about a dozen species possess these structures. So far as we are aware no instance of the discharge of a "luminous cloud" such as observed in several other bathypelagic forms has as yet been recorded for these forms.

The species are most abundant in tropical and sub-tropical areas, being most numerous in the Atlantic between the Tropic of Capricorn and 30° North Latitude. Although fourteen of the sixteen species known from the North Atlantic area were taken by "Atlantis" at Stations 2666 (39° N., 70° W.) and 2667 (35° N., 69° 36′ W.), only three species have been taken by any expeditions north of 47° N. Lat. The horizontal distribution of the species of *Sergestes* is similar to that of other bathypelagic decapods; several species have been taken at numerous localities throughout the world, while others have a restricted distribution with closely related species inhabiting corresponding areas in other oceans.

Comparatively little is known of the vertical distribution of these animals. This is far from surprising when one realizes that previous expeditions have for the most part used open nets, which are perhaps more likely to catch animals when the net is being raised to the surface than at any other time. Also, most expeditions have covered a wide area and an attempt has been made in the reports to combine into one table the depth records for each species from these widely scattered localities. When one considers that probably no condition save pressure is everywhere constant at a given depth; when one realizes that light intensity, temperature, oxygen content and the chemical composition of the water all vary markedly at different localities at a stated depth, it is no less than amazing that certain species are apparently found at so nearly similar depths in all parts of the area in which they are encountered. Until exhaustive collections are made with closing nets at single stations and the results examined separately we will continue to be quite ignorant of the optimum conditions preferred by the various species. Table I gives a very rough idea of the depths at which the various species may be encountered in the area explored by " Atlantis." The records for *S. arcticus* were made at Stations 2463 and 2894, and for *S. mollis* at Stations 2475, 2666, 2667 and 2894; the other " Atlantis " specimens were all taken at Station 2667. Since most of the tows at Station 2667, from which most of the material was obtained, were made only at 400 and 800 meters, very little is known of the lower limits of any of these species. It is hoped that work on " Atlantis " in the near future at Station 2667 in greater depths will make the picture more nearly complete.

TABLE I

Depths in meters at which adult specimens of *Sergestes* have been taken with closing nets by "*Atlantis.*"[2]

	0	200	400	600	800	1000	1200	1400	1600	1800	2000	2050
Sergestes												
mollis[3]........	..	..	..	X	X	X	..	..	X	X	X	X
sargassi........	..	..	X	..	X	..	..	..	X			
pectinatus.....	..	X	X	X	X							
arcticus........	..	X	X	X	X	X						
corniculum.....	..	..	X	..	X							
edwardsi.......	..	..	..	..	X							
cornutus.......	X	..	X									
vigilax.........	X	..	X	..	X	X						
atlanticus......	X	..	X	..	X							
tenuiremis.....	..	..	..	..	X							
grandis........	..	..	X	..	X							
crassus........	..	..	X	..	X							
robustus.......	..	X	X	X	X							

[2] The records of surface catches of adults of *S. atlanticus*, *S. cornutus* and *S. vigilax* have been taken from the reports of other expeditions.

[3] The catches of *S. mollis* at 600, 800 and 1,000 meters were all made at Station 2894. The lower transparency of the water in this region as compared with the Sargasso Sea, where most of the other hauls were made, may account, in part, for this occurrence of *S. mollis* at depths so much shallower than those at which it is usually taken.

EXTERNAL FEATURES OF THE EYES

The accompanying figures (2–9) and Table II illustrate the amount of variation in the eyes of *Sergestes*. Since the body is less compressed and the bases of the antennal scales are broader in these forms than in the acanthephyrids, the eyes are borne on relatively longer stalks to enable the animal to see in all directions when the eyes are extended laterally. Since the length of the carapace is apparently not a constant fraction of the total body length and since such robust species as *S. crassus* have a much shorter carapace in proportion to body size than slender species like *S. corniculum,* it was found that the ratio of the diameter of the cornea to the carapace length showed less clearly the actual comparative sizes of the eyes than did the ratio of the diameter of the cornea to the entire length of the cornea and eyestalk and the portion of the entire cornea and stalk occupied by the cornea. Even the latter comparisons are far from ideal as some species such as *S. arcticus* apparently have a longer stalk than others, but a more trustworthy comparison could not be found. Every part of a prawn which might be compared to the diameter of the eye is found to show some specific variation.

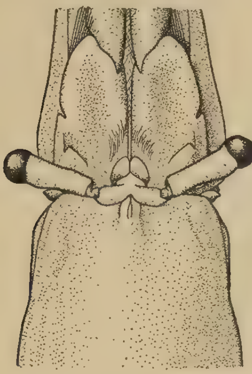
TABLE II

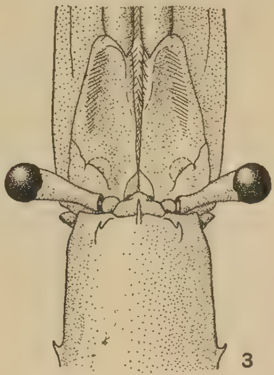
Relative size of the cornea as compared with the length of the carapace and the combined length of eyestalk and cornea in thirteen species of *Sergestes.*

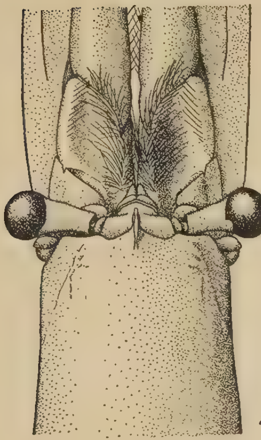
Species	Ratio Diameter of cornea to Length of cornea plus eyestalk	Ratio Length of cornea to Length of cornea plus eyestalk	Ratio Diameter of cornea to Length of carapace
Sergestes			
mollis	0.34	0.25	0.052
sargassi	0.40	0.31	0.085
pectinatus	0.45	0.36	0.099
arcticus	0.46	0.38	0.090
corniculum	0.47	0.43	0.072
edwardsi	0.54	0.37	0.098
cornutus	0.56	0.34	0.092
vigilax	0.57	0.44	0.097
atlanticus	0.58	0.42	0.105
tenuiremis*	0.63	0.53	0.088
grandis*	0.63	0.57	0.081
crassus*	0.65	0.50	0.132
robustus*	0.67	0.67	0.115

* Luminescent species.

It is apparent from the accompanying figures that by far the smallest eyes in proportion to body size are to be found in *S. mollis* (Fig. 2), the only Atlantic species that obviously is restricted, for the most part, below the 1,000 meter zone. This species is a soft-bodied form, red in color, and it recalls to mind *Hymenodora* among the acanthephyrids, although the eyes are far less degenerate than in the latter. One other sergestid, *Petalidium obesum,* very probably inhabits a similar depth and the eyes in it are possibly even smaller than in *S. mollis.* The form with the largest eyes, *S. robustus* (Fig. 5) is not, as might be expected, one of the species that frequents the surface layers. In fact, those four species which have the broadest eyes in proportion to the stalk, *S.*







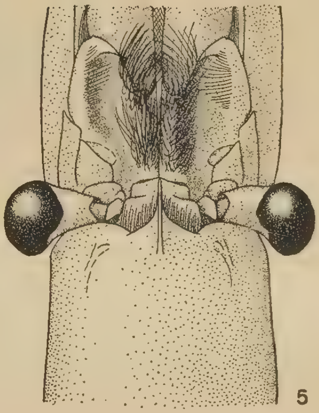


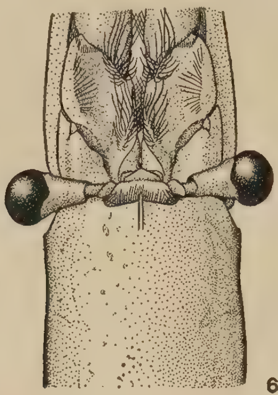
FIG. 2. *Sergestes mollis* Smith, male, 48 mm. in length. A species which is usually taken below the photic zone. Photophores absent. × 5.

FIG. 3. *Sergestes arcticus* Kröyer, male, 40 mm. in length. Photophores absent. × 5.

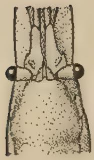
FIG. 4. *Sergestes grandis* Sund, female, 56 mm. in length. Photophores present. × 5.

FIG. 5. *Sergestes robustus* Smith, male, 58 mm. in length. Photophores present. × 5.

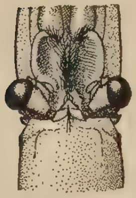
tenuiremis (Fig. 6), *S. grandis* (Fig. 4), *S. crassus* (Fig. 8), and *S. robustus,* are seldom taken in the upper 400 meters. Next in order above these (possibly by chance) are the three species which have been found at the surface, and between this group and *S. mollis* are five species with rather small eyes which, so far as is known, frequent the lower part of the photic zone.[4]



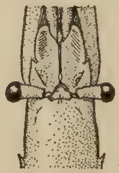
6



7



8



9

FIG. 6. *Sergestes tenuiremis* Kröyer, male, 52 mm. in length. Photophores present. × 5.

FIG. 7. *Sergestes cornutus* Kröyer, female, 14 mm. in length. Photophores absent. × 5.

FIG. 8. *Sergestes crassus* Hansen, male, 24 mm. in length. Photophores present. × 5.

FIG. 9. *Sergestes atlanticus* H. Milne Edwards, female, 18 mm. in length. Photophores absent. × 5.

---

[4] The investigations of Welsh, Chace and Nunnemacher (1937), and more recent unpublished studies, indicate that certain of the sergestids undergo extensive diurnal vertical migrations. The level of maximum numbers of a given species may be between the surface and 200 meters during the night and between 600 and 800 meters during the day. Therefore it is impossible to state that a certain species lives normally at a certain depth, and the most one can say is that the majority of the sergestids live in the photic zone and perhaps only one species in the North Atlantic, *S. mollis,* normally occurs below the level to which light penetrates.

If these figures present a true picture of the relative sizes of the eyes in the various species examined, one would naturally look for some factor to account for the large eyes of the four species at the bottom of the table. We believe that the answer may be found in the possibility that those species possess luminescent organs or photophores.

Until the sergestids of the "Michael Sars" expedition were reported upon by Sund in 1920 there was but one North Atlantic species, *S. splendens* Hansen, which was known to have photophores. Sund mentioned some pigmented spots in three other species, *S. grandis, S. crassus* (=*S. splendens* Sund), and *S. robustus,* which he suggested might be luminous organs. From the material of these three species collected by "Atlantis" we have been able to confirm his observations, and, although no histological preparations have as yet been made of this material, the position of the spots parallels so closely that of the photophores in those species which unquestionably possess them that there seems little doubt that such is their function. *S. crassus* and *S. robustus* apparently have these spots only on the antennal scales and outer uropods, while *S. grandis* (Fig. 1) has them scattered about the body and legs, particularly under the thorax and abdomen. In one large specimen of the latter species no less than 167 of these structures were counted. Hansen (1922) apparently doubted that these spots were actually photophores since they were not equipped with the lens-like structure found in the photophores of most other decapods and so become invisible in specimens preserved in alcohol or for too long in formalin. However, Kemp (1925) has described what he believes to be luminous organs in three species of pandalids from the Indian Ocean and these differ in structure from those which are known of other decapods in lacking any external trace of a lens.

If, then, the assumption is allowed that these structures are luminescent, only *S. tenuiremis* remains of those species which have the ratio of cornea to length of eyestalk greater than 0.60 and the ratio of the length of the cornea to the eyestalk greater than 0.50. Because no luminiscent structures were known in that species, a careful examination of a large male specimen was made. Although the specimen had been in formalin for about seven months and the characteristic red color had consequently disappeared, a pair of large, whitish organs were found in the coxae of the last pair of thoracic legs near the openings of the vasa deferentia. Sections made from one of these organs proved that they were almost certainly a cluster of at least three large photophores with well developed lenses entirely enveloped by the surrounding tissues. Their position and the absence of an external lens closely parallels the structures described by Kemp in the Indian pandalids.

The evidence presented would indicate that there is some correlation between the size of the cornea in the species of *Sergestes* which live near the limit of light penetration and the presence or absence of luminescent organs. In the other five species which are known to have photophores, *S. challengeri* Hansen, *S. fulgens* Hansen, *S. prehensilis* Bate and *S. splendens* Hansen the eyes are described and figured as large, although the figures are usually not sufficiently accurate to permit actual measurements. O. Pesta (1918) described structures on the inner side of the carapace in *S. corniculum* which he suggested might be photophores, but if these spots do prove to be luminous the proposed theory obviously does not hold for this species.[5]

Approximately one half of the described North Atlantic species possess a small tubercle on the inner margin of the eyestalk near the cornea. It may be of interest to list here the species which have or do not have this tubercle, although there seems to be no correlation between the presence or absence of such a structure and the presence or absence of photophores or the size of the cornea.

Tubercle present	Tubercle absent
S. armatus	*S. arcticus*
S. corniculum	*S. atlanticus*
S. crassus	*S. cornutus*
S. grandis	*S. edwardsi*
S. pectinatus	*S. mollis*
S. sargassi	*S. robustus*
S. tenuiremis	*S. splendens*
	S. vigilax

---

[5] According to Burkenroad (1937) Organs of Pesta are probably present in all species of sergestids excepting *S. mollis, S. tenuiremis* and *S. challengeri.*

Figures 10–15 inclusive are all from dorso-ventral sections of eyes, unstained, × 32.

FIG. 10. Photomicrograph of a section of an eye of *Sergestes corniculum* made by means of transmitted light.

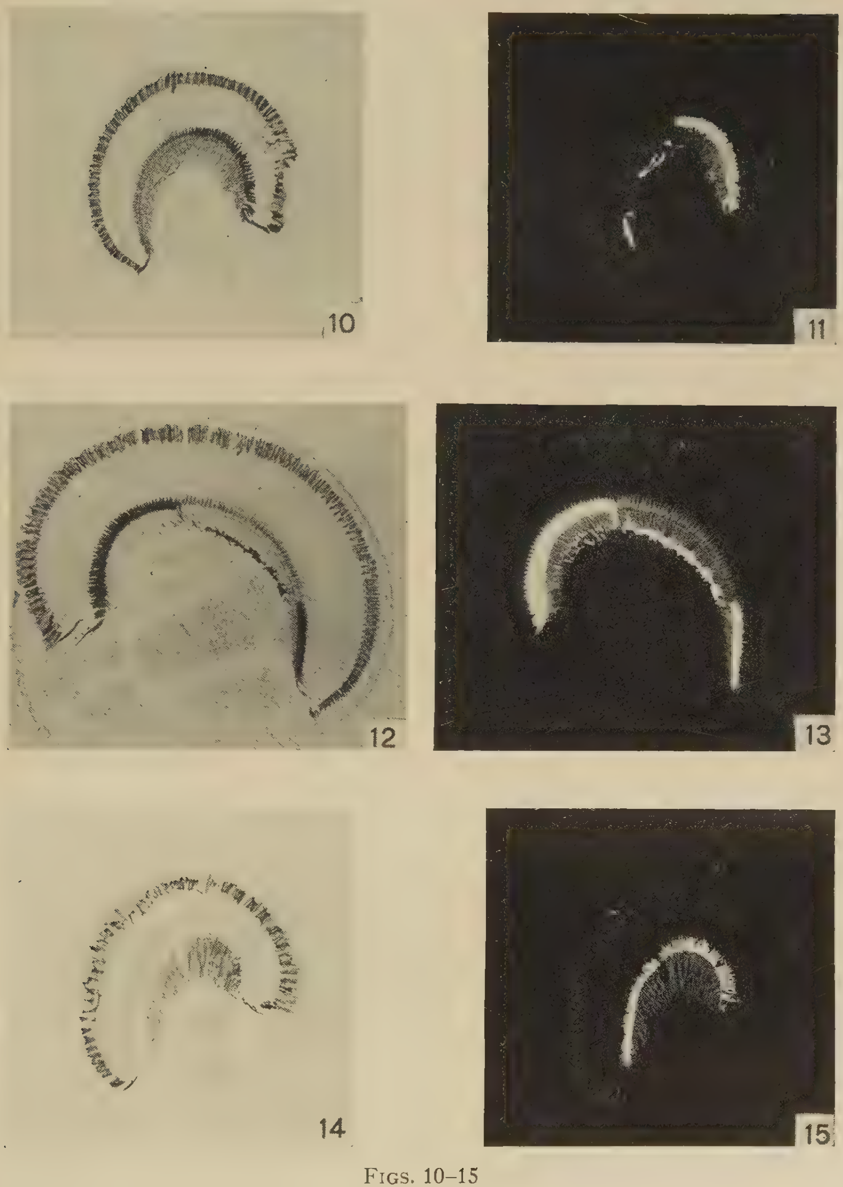
FIG. 11. The same preparation as in Fig. 10 photographed by means of dark-field illumination. The reflecting pigment which is more abundant in the dorsal part of the eye may be readily distinguished from the screening pigment.

FIG. 12. Photomicrograph of a section of an eye of *Sergestes robustus* made by means of transmitted light.

FIG. 13. The same preparation as in Fig. 12 photographed by means of dark-field illumination. The reflecting pigment is more abundant in the dorsal region which is toward the left.

FIG. 14. Photomicrograph of a section of an eye of *Sergestes mollis* made by means of transmitted light.

FIG. 15. The same preparation as in Fig. 14 photographed by means of dark-field illumination. The reflecting pigment is more evenly distributed throughout the region of the eye where it normally occurs.


10
11
12
13
14
15

Figs. 10–15

Structure and Pigmentation of the Eyes

The eyes of eight species of sergestids were sectioned and examined histologically. The structure of these eyes was found to be essentially like that of deep and shallow-water shrimps and prawns whose eyes have been frequently described. One feature common to all was found to be the large and clearly defined rhabdomes, the receptor elements of the eye. The most striking differences were seen in the amounts and distribution of screening and reflecting pigments.

The eyes of *S. grandis* and *S. tenuiremis* resemble those of *S. robustus* (Figs. 12 and 13). It has already been pointed out that these three species possess photophores and this probably accounts for their large eyes. This may also be the reason for the large amount of reflecting pigment found in these eyes. Its distribution is such that the periphery of the eye may be more sensitive to differences in light intensity than the central portion, and the larger amount of proximal pigment in the central portion of the eye may conceivably increase the visual acuity of the region by a partial isolation of the rhabdomes from one another.

S. corniculum (Figs. 10 and 11), *S. arcticus, S. armatus* and *Petalidium obesum* probably do not possess photophores and certain of them may inhabit a region of higher light intensity than the three mentioned above. Of these forms only the first has any reflecting pigment in the eye, the others completely lacking this set of pigment. *S. arcticus* and *P. obesum* have a large amount of black, proximal, screening pigment.

Since *S. mollis* normally lives below the photic zone, as does the acanthephyrid *Hymenodora glacialis,* one might expect to find that its eyes were equally degenerate but such is not the case. They are the smallest, in relation to body size, of all the sergestids examined by us, but structurally the eye shows very little modification which may be correlated with life in a zone to which sunlight does not penetrate (Figs. 14 and 15). The even distribution of reflecting pigment may conceivably be related to the conditions under which the animal lives, but there are fairly large amounts of distal and proximal screening pigments. In *Hymenodora* (Welsh and Chace, 1937) it was shown that screening pigments were completely lacking, the rhabdomes had disappeared and there was an abnormally large amount of reflecting pigment. Hence the eye was considered to be quite degenerate and capable of doing no more than registering changes in light intensity.

Decapod crustaceans which are known with certainty to dwell exclusively in the vast intermediate region of the sea, between the lower limit of the photic zone and the bottom (excepting the bottom fauna), are not numerous as regards species. Until more have been studied it will be impossible to determine the exact trend in the degeneration of the eye as a result of living in complete darkness. From the work thus far carried out, however, it appears that depth, hence light intensity, modifies the eye, but in addition the possession of photophores and the ability to produce light is a most important factor in this adaptation.

SUMMARY

1. Fourteen species of *Sergestes* have been taken in closing nets from the western part of the North Atlantic and the size and structure of their eyes have been related to the depth at which certain species occur and to the presence or absence of photophores.

2. *Sergestes mollis* is ordinarily taken below the photic zone and this species lacks photophores. The corneal portion of the eye of this form is smaller in relation to body size than is that of any other species studied. The eyes, however, are not so degenerate structurally as those of *Hymenodora glacialis,* an acanthephyrid having a similar vertical distribution.

3. *Sergestes tenuiremis, S. grandis, S. crassus and S. robustus* have been shown to possess organs which are probably photophores and these four species have the largest eyes in respect to body size of all which have been studied. Hence it may be concluded that the production of light by such an organism influences in some way the development of the eye. This agrees with the findings on the acanthephyrids.

4. The remainder of the sergestids studied which live within the photic zone have eyes smaller than those which possess photophores and in certain cases (*S. arcticus* and *S. armatus*) the pigmentation of the eye is quite unusual.

LITERATURE CITED

Burkenroad, M. D., 1937. The Templeton Crocker Expedition. XII. Sergestidae (Crustacea Decapoda) from the Lower Californian Region, with descriptions of two new species and some remarks on the Organs of Pesta in Sergestes. *Zoologica, Sci. Contr. N. Y. Zool. Soc.,* **22**: 315.

Hansen, H. J., 1922. Crustacés décapodes (Sergestides) provenant des campagnes des yachts Hirondelle et Princesse-Alice (1885–1915). *Rés. camp. sci. Monaco,* **64**: 1.

Kemp, S., 1925. Notes on Crustacea Decapoda in the Indian Museum. XVII. On various Caridea. *Rec. Ind. Mus. Calcutta,* **27**: 249.

Pesta, O., 1918. Die Decapodenfauna der Adria. Leipzig und Wien.

Sund, O., 1920. Penæides and Stenopides. *Rept. Michael Sars N. Atlantic Deep-Sea Exp., 1910,* **3**: pt. 2 Zool.

Welsh, J. H. and F. A. Chace, Jr., 1937. Eyes of deep-sea crustaceans. I. Acanthephyridae. *Biol. Bull.,* **72**: 57.

Welsh, J. H., F. A. Chace, Jr., and R. F. Nunnemacher, 1937. The diurnal migration of deep-water animals. *Biol. Bull.,* **73**: 185.

Contribution No. 177

Eddy Diffusion at Mid-Depths in the Caribbean Sea Region.

By

H. R. Seiwell.[1]

1. Vertical Diffusion in the Caribbean Basin.

THE extensive distribution and close vertical relationship of the principal salinity and oxygen minima in the Caribbean Sea region[2] provides a convenient basis for estimation of the magnitude of eddy diffusion at mid-depths in that region. In the following procedure the approximate average value of the mean vertical eddy coefficient in a layer (approximately 100 metres thick) between the minimum oxygen and minimum salinity concentrations in the eastern part of the Caribbean basin (based on "Atlantis" stations 1492—1504, section I, and 1505—1515, section II) is calculated. It is assumed, for purposes of calculation, that only small vertical variations of horizontal velocity occur within the stratum concerned, and, also, as a first approximation, it was further assumed that the only eddy component producing a measurable diffusion effect was that acting along the vertical. Hence, changes in concentration of the minimum oxygen value (Fig. 1) between sections I and II are considered to result from the combined effects of biological activity and vertical eddy diffusion[3], whereas changes in concentration of the salinity minimum (Fig. 2) are considered to be due solely to vertical diffusion.

---

[1] Contribution No. 177 from the Woods Hole Oceanographic Institution.

[2] A discussion of this situation is found in "Application of the Distribution of Oxygen to the Physical Oceanography of the Caribbean Sea Region," by H. R. Seiwell. To be published in *Papers in Physical Oceanography and Meteorology* as Contribution No. 162 from the Woods Hole Oceanographic Institution.

[3] Between sections I and II the average concentration of the oxygen minimum decreased, showing an excess of consumption by biological activity over that gained by turbulence.

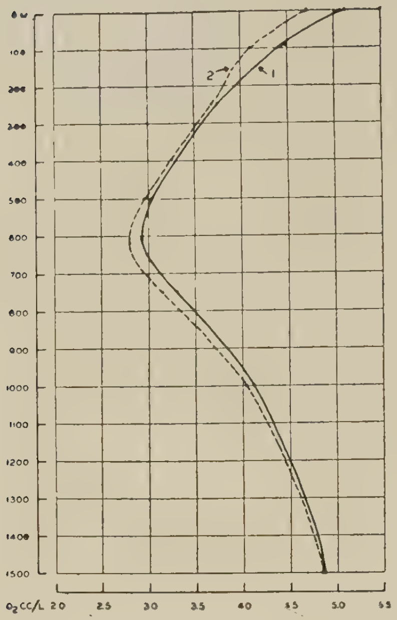


Fig. 1. Mean vertical distribution of oxygen (c.c. per litre) for section I (stations 1492—1504) and section II (stations 1505—1515) in the eastern part of the Caribbean basin.

The consumption of oxygen at the depth of its minimum concentration during the time (t) it takes this water to move horizontally from section I to II would be:

$$Ct = O_1 - O_2 + \frac{\Delta O}{\Delta t}\,t$$

where C is the rate of oxygen consumption per unit time, $O_1 - O_2 =$ the difference in the observed mean minimal oxygen concentrations of sections I and II, and $\frac{\Delta O}{\Delta t}$ is the amount of oxygen supplied per unit time due to vertical mixing (changes due to the lateral eddy components were neglected). We get from the general equation for vertical diffusion:

$$(1) \qquad \frac{\Delta O}{\Delta t} = \frac{A}{\varrho}\,\frac{\delta^2 O}{\delta Z^2}$$

and, thence, by substitution:

$$(2) \qquad O_1 - O_2 + t\left(\frac{A}{\varrho}\,\frac{\delta^2 O}{\delta Z^2} - C\right) = 0$$

This equation contains two unknowns, t and A, and was solved by a consideration of the minimum salinity concentrations at mid-depths of sections I and II (as represented by stations 1499 and 1510, Fig. 2). Thus, the application of Jacobsen's equation[4] to the temperature-

---

[4] Jacobsen, J. P. "Eine graphische Methode zur Bestimmung des Vermischungskoeffizienten im Meere." Gerl. Beitr. zur Geophysik, Vol. XVI, pp. 404—412.

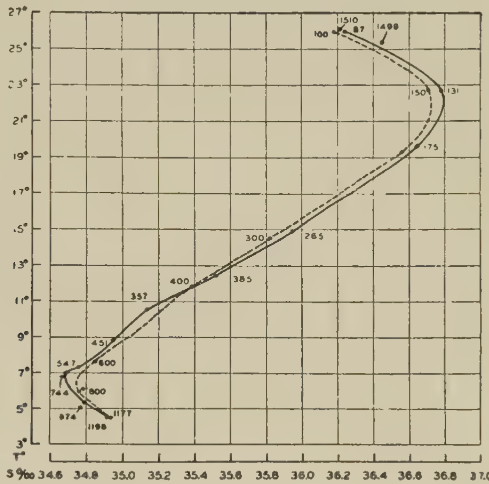


Fig. 2. Temperature-salinity relations for stations 1499 and 1510 in the eastern part of the Caribbean basin.

salinity relationship of the strata adjacent to the salinity minima of stations 1499 and 1510 (assuming a steady state as the water moves from section I to II) would give:[5]

$$t\frac{A}{\varrho}=\frac{S^2}{8} \tag{3}$$

It may be accepted that the relative functional relationships of temperature and salinity of sections I and II, in the vicinity of the salinity minimum, are represented with sufficient accuracy by those for stations 1499 and 1510 (which lay at approximately mid-points of their respective sections), and there is no need to use mean values for the entire sections as was done for the less accurate oxygen values. Equations (2) and (3) may be combined into a simultaneous system and solved for t and A (on the basis of previous assumptions these quantities both in equation (2), involving the minimum oxygen concentration, and equation (3), involving the minimum salinity concentration, are taken to be equivalent), thus:

$$t\left[\frac{A}{\varrho}\frac{\delta^2O}{\delta Z^2} \quad C\right] = O_2 - O_1$$

$$t\frac{A}{\varrho} = \frac{S^2}{8}$$

which gives on solving:

$$t=\frac{O_1-O_2}{C}+\frac{\delta^2O}{\delta Z^2}\frac{S^2}{8C} \tag{4}$$

Equation (4) may be evaluated with the aid of data plotted in Figures 1 and 2. The difference in mean minimum concentration

---

[5] The density of sea water ($\varrho = 1{\cdot}02$, approximately) is not utilized in the practical application of the diffusion equations.

$(O_1 - O_2)$ between sections I and II was 0·16 c.c per litre = $1{\cdot}6 \times 10^{-4}$ cm.^{3} g.$^{-1}$ and the mean value of $\frac{\delta^2 O}{\delta Z^2}$ at 615 metres (mean depth of oxygen minimum concentration) for sections I and II, was:

$$\frac{\delta^2 O}{\delta Z^2} \quad 2.40 \times 10^{-12} \text{ cm.}^3 \text{ g. }{}^{1} \text{cm.}^{-2}$$

The value, $S = 2{\cdot}25 \times 10^4$ centimetres, was determined graphically from the combined temperature-salinity relationships of stations 1499 and 1510 (Fig. 2). The value of oxygen consumption per unit time, C, was taken to be $1{\cdot}35 \times 10^{-11}$ cm.^{3} g.$^{-1}$sec.$^{-1}$ (0·42 cc. per litre per year), the mean value of oxygen consumption previously calculated for the oxygen-poor layer at mid-depths of the tropical mid-Atlantic[6]).

Substitution of these values in equation (4) would give:

$$t = 2{\cdot}3 \times 10^7 \text{ sec.} = 0{\cdot}7 \text{ year}$$

and the mean vertical eddy diffusion coefficient characterizing the water column at mid-depths, between the salinity and oxygen minimum in the eastern Caribbean, would then be:

$$A = 2{\cdot}8 \text{ C.G.S. units.}$$

The distance, X, between stations 1499 and 1510 (both of which are located near the mid-points of their respective sections) is approximately the same as the mean distance between sections I and II, or $X = 4{\cdot}45 \times 10^7$ centimetres. Thus, the mean horizontal velocity in the layer bounded by minimum salinity and minimum oxygen concentrations was calculated to be:

$$\mu = \frac{\Delta x}{\Delta t} = 2{\cdot}0 \text{ cm.sec.}^{-1}.$$

Due to the various assumptions involved (the effect of horizontal eddy diffusion was entirely neglected), the values for A and μ are considered to be only approximate, but they are probably of the correct order of magnitude; the value of $A = 2{\cdot}8$ C.G.S. units is within the limits established by other investigations for the vertical eddy diffusion coefficient at mid-depths.

The plausibility of the calculated values for A and μ may be tested in a manner similar to that used by Defant[7]) for estimating the relation of the eddy coefficient to the horizontal velocity in the deeper parts of the South Atlantic. On assumption of steady motion, the existence of the relation involving only the vertical eddy component,

---

[6]) See Seiwell, H. R.: "The distribution of oxygen in the western basin of the North Atlantic." Papers in Phys. Ocean. and Meteorol., Vol. III, No. 1. 86 pp. 1934.

[7]) Defant, Albert. "Zur Dynamik des Antarktischen Bodenstromes im Atlantischen Ozean." Zeitschr. für Geophysik, Vol. XI, pp. 50—55.

(5) $$\frac{A}{\mu} = \varrho \frac{\frac{\delta \alpha}{\delta x}}{\frac{\delta^2 \alpha}{\delta Z^2}}$$

allows calculation of the ratio, $\frac{A}{\mu}$, where $\frac{\delta \alpha}{\delta x}$ denotes horizontal variation of the conservative property, α, in the direction of flow and $\frac{\delta^2 \alpha}{\delta Z^2}$ the curvature of its vertical variation; the co-ordinate system being oriented so that the X-axis points in the direction of flow, velocities in all other directions are assumed to be zero. Thus, application of equation (5) to salinity data from the vicinity of the salinity minima of stations 1499 and 1510 (Fig. 2) gives:

$$\frac{A}{\mu} = \frac{1 \cdot 35 \times 10^{-12}}{10^{-12}} = 1 \cdot 35.$$

as the ratio existing in the vicinity of the salinity minimum; this result is in good agreement with the ratio, $\frac{A}{\mu} = \frac{2 \cdot 8}{2 \cdot 0} = 1 \cdot 4$, from results of the previous calculation in the vicinity of the oxygen minimum.

Further application of the fundamental differential equation regulating diffusion of substances in the sea by vertical turbulence alone (equation 1) to the temperature and salinity data in the vicinity of the oxygen minimum at stations 1499 and 1510 supports the value, $A = 2 \cdot 8$ C.G.S. units, as approximately correct for the existing circumstances. Thus, denoting observed temperature (t°) and salinity (S) values (at the depth of the oxygen minimum) for station 1499 (section I) by the subscript 1 and for station 1510 (section II) by the subscript 2, we have:

$$S_2 - S_1 = 9 \times 10^{-5} \text{ g. g.}^{-1}$$
$$t_2^\circ - t_1^\circ = 3 \cdot 5 \times 10^{-1} \text{ deg.}$$

showing that increases both in salinity and temperature have taken place by mixing processes as the water at mid-depths (at depth of the principal oxygen minimum) near the central axis of the Caribbean basin, moves westward from station 1499 (section I) to station 1510 (section II). The average oxygen content at the depth of its minimum concentration actually decreased between sections I and II, showing an excess of oxygen consumption (by biological processes) over that gained by mixing; the mean difference in oxygen content between sections I and II was calculated to be:

$$O_2 - O_1 = -1 \cdot 6 \times 10^{-4} \text{ cm.}^3 \text{ g.}^{-1}$$

Mean values for the second derivatives of the vertical salinity, temperature, and oxygen gradients for stations 1499 and 1510 at the depth of the oxygen minimum concentration were:

$$\frac{\delta^2 S}{\delta Z^2} = 10\cdot0 \times 10^{-13}\ \text{g}\cdot\text{g.}^{-1}\ \text{cm.}^{-2}$$

$$\frac{\delta^2 t^\circ}{\delta Z^2} = 5\cdot7 \times 10^{-9}\ \text{deg. cm.}^{-2}$$

$$\frac{\delta^2 O}{\delta Z^2} = 2\cdot4 \times 10^{-12}\ \text{cm.}^3\ \text{g.}^{-1}\ \text{cm.}^{-2}$$

And the time rates of changes as computed from the equation

$$\frac{d\alpha}{dt} = \frac{A}{\varrho}\,\frac{\delta^2\alpha}{\delta Z^2} \tag{6}$$

when $A = 2\cdot8$ C.G.S. units, are:

$$\frac{ds}{dt} = 2\cdot80 \times 10^{-12}\ \text{g. g.}^{-1}\ \text{sec.}^{-1}$$

$$\frac{dt^\circ}{dt} = 1\cdot60 \times 10^{-8}\ \text{deg. sec.}^{-1}$$

$$\frac{dO}{dt} = 6\cdot74 \times 10^{-12}\ \text{cm.}^3\ \text{g.}^{-1}\ \text{sec.}^{-1}$$

Integrating between the limits, $t = 0$ and $t = 2\cdot3 \times 10^7$ seconds (the time calculated for the water to move from station 1499 to 1510, page 158), gives the amount of change in temperature, salinity, and oxygen resulting from vertical diffusion as the water at the depth of the oxygen minimum moves from station 1499 to 1510 (the results are entered in Table 1).

Table 1.

Property	Observed change	Calculated change	Computed — Observed
Oxygen	$-1\cdot6 \times 10^{-4}$	$1\cdot5 \times 10^{-4}$	$3\cdot1 \times 10^{-4}$ cm.^{3} g.$^{-1}$
Temperature . .	$3\cdot5 \times 10^{-1}$	$3\cdot7 \times 10^{-1}$	2×10^{-1} deg.
Salinity	$9\cdot0 \times 10^{-5}$	$6\cdot4 \times 10^{-5}$	$-2\cdot6 \times 10^{-5}$ g. g.$^{-1}$

Comparison of observed and calculated change in concentration of identifying properties at depth of minimum oxygen concentration between stations 1499 and 1510 in Caribbean basin. Difference between computed and observed oxygen values represents the approximate amount of oxygen consumed by biological processes between section I and II. Thus: $\frac{3\cdot1 \times 10^{-4}}{2\cdot3 \times 10^{7}}\,\frac{\text{cm.}^3\ \text{g.}^{-1}}{\text{sec.}} = 1\cdot35 \times 10^{-11}\ \text{cm.}^3\text{g.}^{-1}\text{sec.}^{-1}$

The agreement between observed and calculated change in the two conservative properties (temperature and salinity) is sufficiently good to substantiate the approximate correctness of the value 2·8 C.G.S. units for the vertical eddy transfer coefficient.

2. Lateral Diffusion in the Caribbean Basin.

In the above discussion of eddy diffusion, only the effects produced by vertical components of turbulent motion have been considered; any effect from lateral turbulence has been neglected in order to simplify the treatment. Likewise, more information is available on the lateral diffusion accompanying fluid motion of the atmosphere than of the ocean, and, in the former, the order of magnitude of horizontal diffusivity coefficients has been calculated to be (according to investigations of Defant[8]), and Richardson and Proctor[9]), approximately between 10^{11} and 10^9 $cm^2. sec.^{-1}$ or expressed as eddy viscosities approximately between 10^8 and 10^6 $g. cm.^{-1} sec.^{-1}$. In the ocean, the effects of the two lateral diffusion components (down-stream and cross-stream components) and of the vertical diffusion component have not been isolated and separately studied, but it is evident (at least in so far as the Caribbean basin is concerned) from a study of the vertical and horizontal gradients of the transferable substances[10]) that to be significant in diffusing substances the lateral turbulent components must exceed greatly the magnitude of the vertical diffusion component.

In connexion with the present investigation of turbulent transfer in the Caribbean basin it is desirable to consider the horizontal as well as the vertical gradients of the available identifying properties in order that comparison of their respective curvatures may furnish information on the magnitude of the horizontal diffusivity coefficients required to produce a measurable effect in their concentrations as a result of lateral diffusion. With this object horizontal and vertical distributions of oxygen, salinity, and temperature at the depth of the minimum oxygen concentration in the vicinity of stations 1499 and 1510 have been compared. The density of the minimum oxygen concentration in the area concerned is reasonably constant.

We are now concerned with the fundamental differential equation, regulating diffusion in the sea both by lateral and vertical turbulence, which may be written:

$$\varrho \frac{d\alpha}{dt} = \frac{\delta}{\delta Z}\left(A \frac{\delta\alpha}{\delta Z}\right) + \frac{\delta}{\delta x}\left(A_1 \frac{\delta\alpha}{\delta x}\right) + \frac{\delta}{\delta y}\left(A_2 \frac{\delta\alpha}{\delta y}\right) \tag{7}$$

The last two terms of the right-hand side referring to the down-stream and cross-stream components may be combined into an average value for the lateral component so that the equation would read:

$$\varrho \frac{d\alpha}{dt} = A \frac{\delta^2\alpha}{\delta Z^2} + A' \frac{\delta^2\alpha}{\delta N^2} \tag{8}$$

where A' represents an average value for the two lateral turbulent components and $\frac{\delta^2\alpha}{\delta N^2}$ the average horizontal gradient over a constant density surface. Values of $\frac{\delta^2\alpha}{\delta Z^2}$ have been given previously for oxygen, $\frac{\delta^2 O}{\delta Z^2}$, salinity, $\frac{\delta^2 S}{\delta Z^2}$, and temperature, $\frac{\delta^2 t^\circ}{\delta Z^2}$, at the depth of the oxygen minimum concentration between stations 1499 and 1510; and mean values for the second derivative of the horizontal gradient, $\frac{\delta^2\alpha}{\delta N^2}$, with reference to the same depth are given in Table 2.

---

[8]) Defant, Albert. “Die Zirkulation der Atmosphäre in den gemässigten Breiten der Erde.” Geogr. Annaler, 3, pp. 209—265, 1921.

[9]) Richardson, Lewis F., and Proctor, Denis. “Diffusion over distances ranging from 3 km. to 86 km.” Mem. Royal Meteorol. Soc., Vol. I, No. I, pp. 1—16, 1926.

[10]) See reference in footnote 2, p. 155.

Table 2.

Property	$\frac{\delta^2\alpha}{\delta N^2}$	Ratio: $\frac{\delta^2\alpha}{\delta Z^2} \Big/ \frac{\delta^2\alpha}{\delta N^2}$
Oxygen ...	$\frac{\delta^2 O}{\delta N^2} = 2 \cdot 15 \times 10^{-18}$ cm.^{3} g.$^{-1}$ cm.$^{-2}$	$\frac{\delta^2 O}{\delta Z^2} \Big/ \frac{\delta^2 O}{\delta N^2} = 1 \cdot 1 \times 10^6$
Salinity ...	$\frac{\delta^2 S}{\delta N^2} = 1 \cdot 75 \times 10^{-18}$ g. g.$^{-1}$ cm.$^{-2}$	$\frac{\delta^2 S}{\delta Z^2} \Big/ \frac{\delta^2 S}{\delta N^2} = 5 \cdot 7 \times 10^5$
Temperature	$\frac{\delta^2 t^\circ}{\delta N^2} = 6 \cdot 85 \times 10^{-15}$ deg. cm.$^{-2}$	$\frac{\delta^2 t^\circ}{\delta Z^2} \Big/ \frac{\delta^2 t^\circ}{\delta N^2} = 8 \cdot 4 \times 10^5$

Since the ratios of the second derivatives of mean vertical to mean horizontal gradients at the oxygen minimum concentration are of the order of magnitude of 10^6, a horizontal eddy diffusion coefficient having a value up to 10^5 may exist, and yet produce no measurable effect in the concentrations of the transferable substances. Thus, for example, the amounts of change in concentrations of oxygen, salinity, and temperature, calculated from a horizontal eddy diffusing coefficient of 10^5 C.G.S. units (based on data in Table 2) for the time interval as the water at the depth of the minimum oxygen concentration moves (along an isopycnal surface) from station 1499 to 1510 are given in Table 3. The results are also expressed as percentages of the observed change of concentration ($\alpha_2 - \alpha_1$) and of the change brought about by vertical turbulence (taking $A = 2{\cdot}8$ C.G.S. units). In all cases for this area, the horizontal diffusion which might be brought about by a lateral turbulent coefficient approximately 10^5 times the vertical component is slight.

Table 3.

Property	$10^5 \int_0^{2.3 \times 10^7} \frac{\delta^2\alpha}{\delta N^2} dt$	$100 \frac{\alpha \text{ lateral}}{\alpha \text{ observed}}$	$100 \frac{\alpha \text{ lateral}}{\alpha \text{ vertical}}$
Oxygen	$4 \cdot 95 \times 10^{-6}$ cm.^{3} g.$^{-1}$	—	3 %
Salinity	$4 \cdot 03 \times 10^{-6}$ g. g.$^{-1}$	4 %	6 %
Temperature	$1 \cdot 57 \times 10^{-2}$ deg.	4 %	4 %

Calculation of the amount of lateral diffusion brought about by a lateral eddy coefficient of 10^5 at the depth of the minimum oxygen concentration (calculated from data in Table 2) as the water moved from station 1499 to 1510 ($t = 2{\cdot}3 \times 10^7$ sec.).

Thus, while the above calculations do not necessarily demonstrate the existence of horizontal diffusion they do suggest that horizontal diffusion coefficients of order of magnitude of 10^5 may exist (at the depths concerned) without producing a measurable diffusion effect.

Contribution No. 179

Vol. VI, Art. 4.

FURTHER OBSERVATIONS ON THE HYDROGRAPHY OF THE EASTERN CARIBBEAN AND ADJACENT ATLANTIC WATERS*

By Albert Eide Parr

Bingham Oceanographic Laboratory

INTRODUCTION

In the observations made by the "Atlantis" in the eastern Caribbean during 1933, two interesting possibilities, requiring further investigation, seemed indicated, and in January 1937 an effort was made to obtain the necessary additional information during another cruise of the same research ship, jointly sponsored by the Woods Hole Oceanographic Institution and the Bingham Oceanographic Foundation of Yale University.

The first problem of the renewed investigation referred to the great discrepancy found to exist between the surface salinities determined within the eastern Caribbean during the 1933 cruise and those previously recorded by Jacobsen and others from the adjacent parts of the open Atlantic in the approach of the north equatorial current towards the Lesser Antilles (Parr 1937). On this point the new data provide a most valuable comparison with the previous observations.

The second purpose to be served by the 1937 visit to the eastern Caribbean was that of investigating further the possibility that this hydrographic region, when adequately examined, might provide a particularly instructive case for a study in nature of the relationship between vertical stability and lateral mixing. With reference to its primary objective, this second aspect of the new investigation has proved rather disappointing. Instead of giving sharper definitions of the mixing relationship, the more extensive material mainly shows a greater complication of detail; which was, of course, an equally probable expectation. It seems indicated that this type of problem must either be approached with a much closer spacing of observations, which under practical circumstances means on a much smaller scale,

---

* Joint contribution from Woods Hole Oceanographic Institution (No. 179) and Bingham Oceanographic Foundation, Yale University.

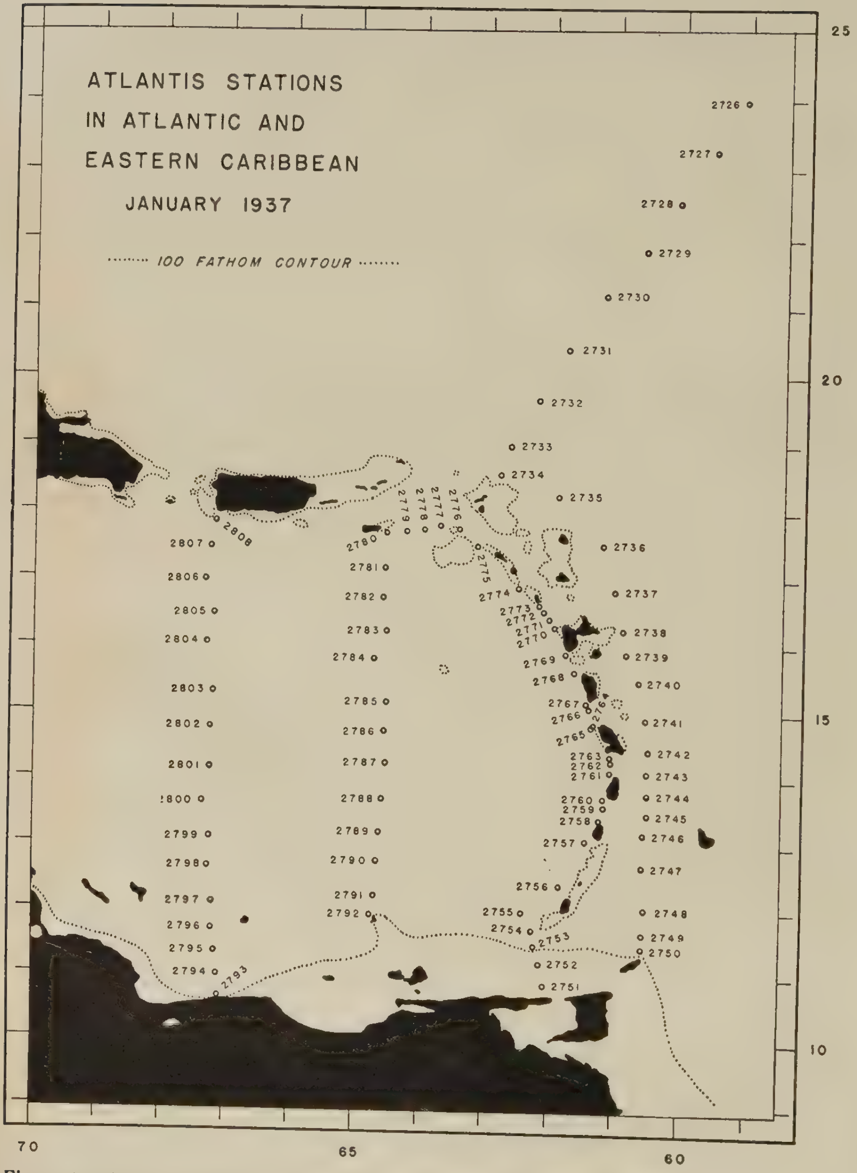

ATLANTIS STATIONS
IN ATLANTIC AND
EASTERN CARIBBEAN
JANUARY 1937
100 FATHOM CONTOUR
2726
2727
2728
2729
2730
2731
2732
2733
2734
2735
2736
2737
2738
2739
2740
2741
2742
2743
2744
2745
2746
2747
2748
2749
2750
2751
2752
2753
2754
2755
2756
2757
2758
2759
2760
2761
2762
2763
2764
2765
2766
2767
2768
2769
2770
2771
2772
2773
2774
2775
2776
2777
2778
2779
2780
2781
2782
2783
2784
2785
2786
2787
2788
2789
2790
2791
2792
2793
2794
2795
2796
2797
2798
2799
2800
2801
2802
2803
2804
2805
2806
2807
2808
25
20
15
10
70
65
60

Figure 1. Atlantis stations in Eastern Caribbean and adjacent waters in January 1937

or by experimental methods. Nevertheless, the 1937 observations from the eastern Caribbean provide us with some very interesting material for synoptic studies of the distribution of the water masses and of their relationships, which will be briefly presented and discussed in this report.

Since both projects of the eastern Caribbean investigation required comparisons with the adjacent waters of the open Atlantic, a series of observations were also made outside of the Antillean Islands, and the positions of all stations are indicated in the accompanying Fig. 1.

ACKNOWLEDGEMENTS

The writer wishes to express his indebtedness to Mr. Alfred Woodcock, of the Woods Hole Oceanographic Institution, who was in charge of observations in the Eastern Caribbean, to Mr. F. S. McMurray, captain of the "Atlantis," to the entire ship's company and to his assistants in the Bingham Oceanographic Laboratory for their splendid cooperation in carrying out the work at sea and completing the analysis of the data at home.

NOTICE

In so far as they are not published in table form in the various reports issued in this series or in the Bulletin Hydrographique published by the Conseil Perm. Intern. Expl. de la Mer, copies of the original records of hydrographic observations made by the research ship "Atlantis" on cruises undertaken under the joint sponsorship of the Woods Hole Oceanographic Institution and the Bingham Oceanographic Laboratory of Yale University may be obtained by application to either of these institutions.

SURFACE AND SUBSURFACE SALINITIES

Figures 2 and 3 give the distribution of surface salinities and of salinities recorded at the first observation below the surface (25 meters intended depth) during 1937. Figure 4 (a reproduction of Fig. 39, Parr 1937) gives the distribution of salinities in the "surface layer" in 1933, corresponding to the subsurface salinity chart for 1937 shown in Fig. 3 (see Parr 1937, p. 5).

The ribbon of high surface salinities along the South American coast of the Eastern Caribbean observed in 1933 (Fig. 4) is equally well in evidence in the 1937 observations (Figs. 2 and 3), and it is mainly due to the transverse (North-South) slope of the entire system, which brings the maximum salinity layer

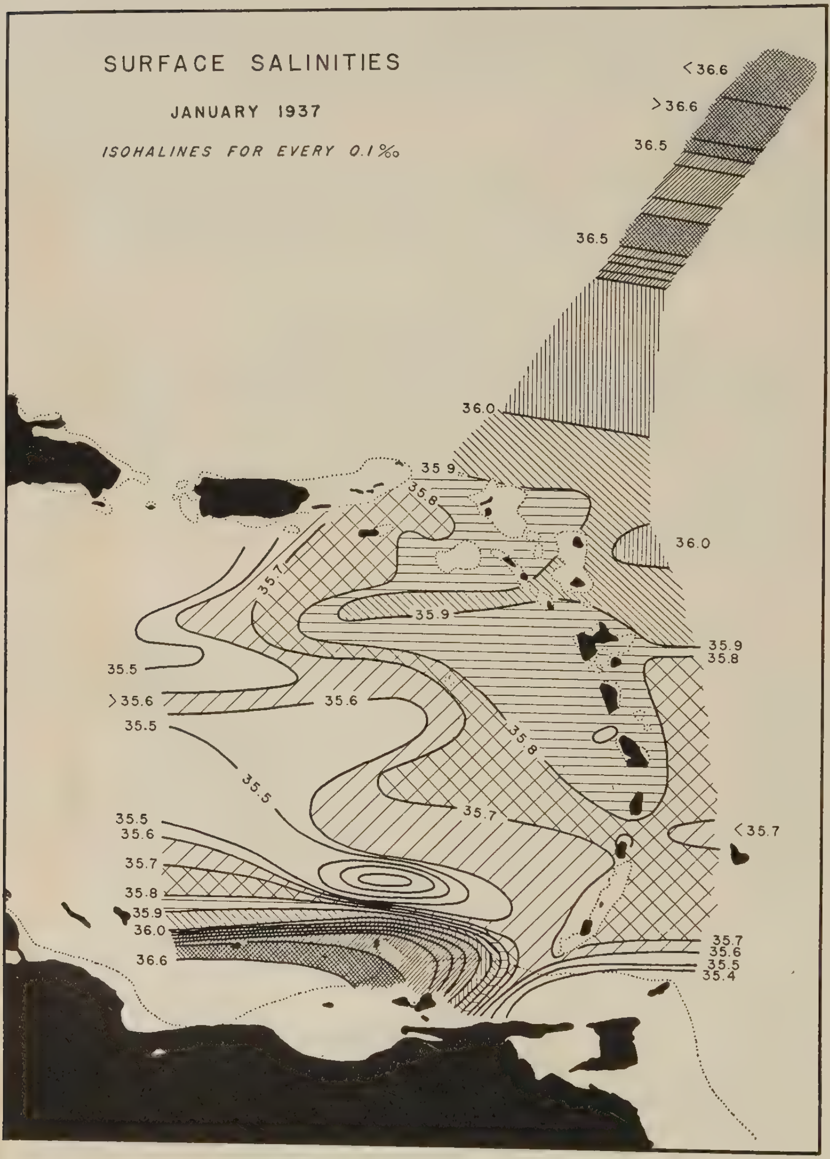

SURFACE SALINITIES
JANUARY 1937
ISOHALINES FOR EVERY 0.1‰
<36.6
>36.6
36.5
36.5
36.0
35.9
35.8
36.0
35.7
35.9
35.9
35.8
35.5
>35.6
35.6
35.5
35.8
35.5
35.7
35.5
35.6
35.7
35.8
35.9
36.0
36.6
<35.7
35.7
35.6
35.5
35.4

Figure 2. Surface salinities. Atlantis observations in January 1937.

almost to the surface on the southern side. Otherwise the 1937 observations show some very interesting variations from the situation observed in 1933. In the latter year no subsurface salinities lower than 36.00°/oo were found in the series south from Virgin Islands, while the same profile in 1937 shows subsurface salinities of 35.5–35.6°/oo in its middle portion and an isolated observation of surface salinities between 35.1 and 35.2°/oo near its southern end. In the eastern series from 1937, salinities lower than 35.6°/oo occurred both immediately outside and immediately inside the Antilles in the southern passage between Trinidad and Grenada. On the northern shelf immediately off Trinidad there is also a single surface observation of 34.57°/oo and a questionable determination of 30.73°/oo, but these are probably without great quantitative significance; and 35.5°/oo can perhaps be set as the minimum significant surface salinity observation in 1937. This salinity, however, is .5°/oo lower than the minimum significant surface salinity observed in 1933, and therefore in somewhat better agreement with the average salinities (34.85°/oo at the surface and 35.14°/oo at 25 meters) reported by Jacobsen (1929) from area XIV in the north equatorial current approaching the Antillean Islands. A considerable difference still remains, however, and it is rather in the comparison of the distributions of surface and subsurface salinities in the Eastern Caribbean in 1933 and 1937, than in their absolute values, that our interest lies. When Figs. 3 and 4 are compared, it seems indicated that the surface water in the Eastern Caribbean may have been derived from quite different directions, by entirely different routes of invasion, in the two years. In 1933 (Fig. 4) we find a broad area of relatively saline (36.2–36.4°/oo) surface water which has apparently entered over a wide front, mainly through the northeast passages of which, unfortunately, only the Anegada Passage was subject of observation in that year. In 1937 the northern part of the Eastern Caribbean contained neither surface nor subsurface waters with salinities as high as 36.0°/oo and the distribution pattern is entirely different from that of 1933, without indication of invasion through Anegada Passage, but with a rather narrow tongue of salinities between 35.9 and 36.0°/oo extending inward from the east between Antigua and Dominica; while a tongue of low salinity surface waters entering through the southern passages between the Lesser Antilles expand greatly to the northwest in their further westward flow. It thus seems indicated that the Eastern Caribbean in 1933 was largely covered by a surface layer of northern and northeastern origin, contrary to conditions in 1937, when the surface waters in this region mainly derived from the southeast with only a relatively small contribution through the more northern passages (excluding the Anegada?). Taking into account the much lower surface salinities found in the Western Caribbean and in the Cayman Sea in 1934 than in 1933 (see Parr 1937, Figs. 39 and 40, pp. 54–55), and the good agreement between the absolute values of 1934 and the Eastern Caribbean records from 1937, it seems probable that the 1937 situation in the Eastern Caribbean is likely to be more typical of the region than that observed in 1933.

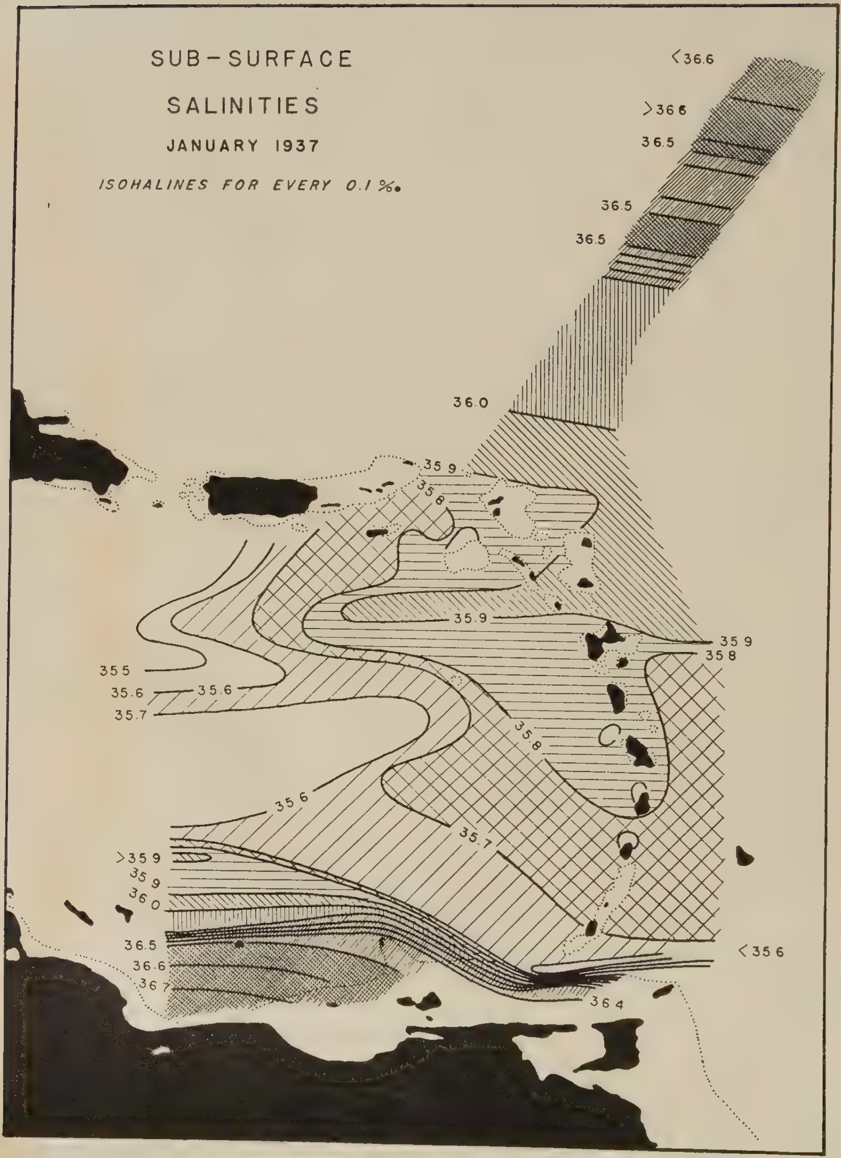

SUB-SURFACE
SALINITIES
JANUARY 1937
ISOHALINES FOR EVERY 0.1 ‰.
<36.6
>36.6
36.5
36.5
36.5
36.0
35.9
35.8
35.9
35.9
35.8
35.5
35.6
35.6
35.7
35.8
35.6
35.7
>35.9
35.9
36.0
36.5
36.6
36.7
36.4
<35.6

Figure 3. Subsurface salinities recorded at first observation below the surface. January 1937.

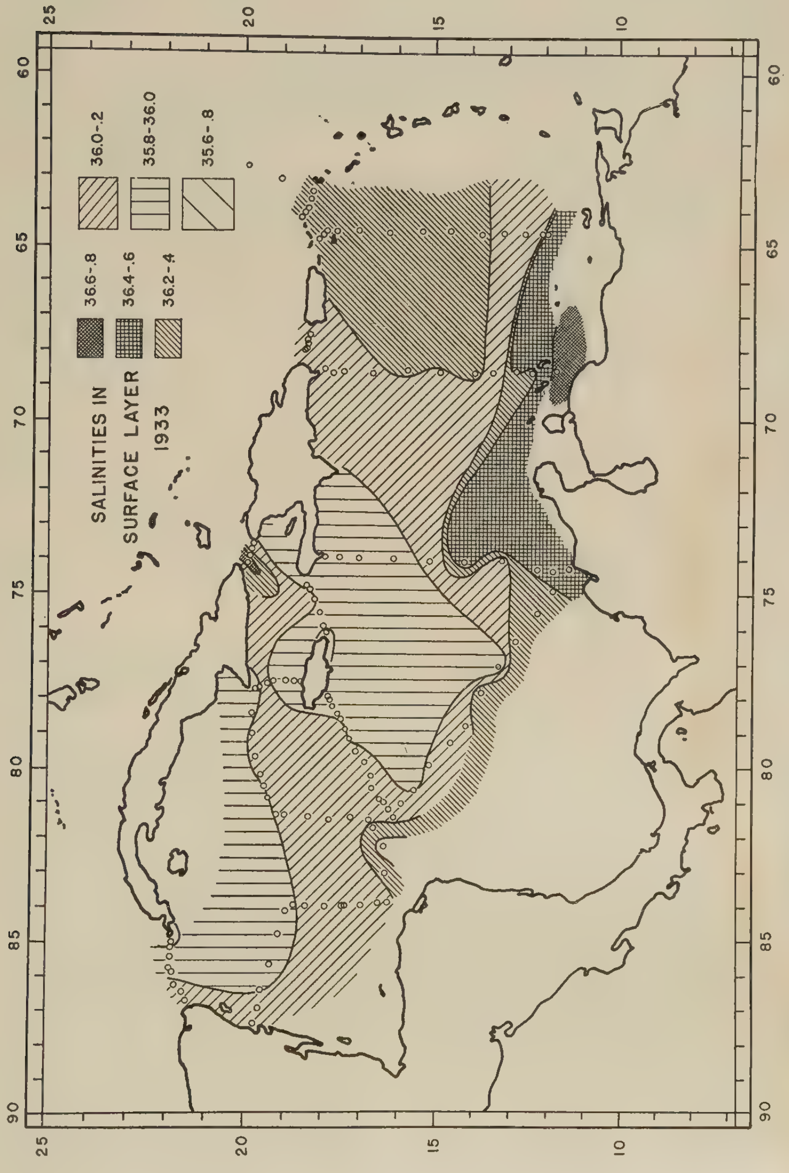

SALINITIES IN
SURFACE LAYER
1933
36.6-.8
36.4-.6
36.2-.4
36.0-.2
35.8-36.0
35.6-.8
25
20
15
10
60
65
70
75
80
85
90

Figure 4. Subsurface salinities in Caribbean and Cayman Sea in 1933. From Parr, 1937, fig. 39.

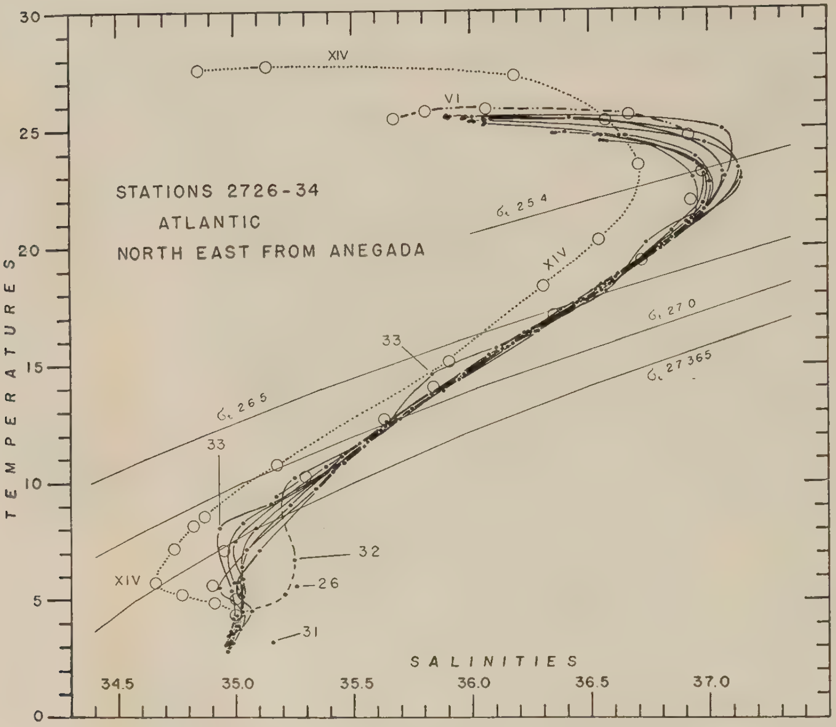


Figure 5. Temperature-Salinity correlations in the southwestern Sargasso Sea northeast from the Antillean Islands. Jacobsen's average T–S correlation values for area VI (southern Sargasso Sea) and XIV (North Equatorial Current, western end) are indicated for comparison by open circles connected with — · · — —· · (VI) or . . . . (XIV). Isopycnals for σ_t 25.4; 26.5, 27.0 and 27.365 are entered to identify the intercepts on which the synoptic charts of the corresponding isopycnic surfaces (figs. 12–15) are based. T–S correlations which have been considered unreliable are connected by broken lines only or left isolated.

IDENTITIES AND RELATIONSHIPS OF WATER MASSES

A secondary purpose of the 1937 cruise was to attempt to trace closer to its origin the shuffling of Sargasso Sea maximum salinity waters in between surface and minimum salinity layers derived from the North Equatorial Current. The probable occurrence of this phenomenon was first suggested by Nielsen (1925) and was found to be confirmed by the "Atlantis" observations of 1933 (Parr 1937, p. 82 and 85). In Figs. 5–7 the T–S correlations in the 1937 profile through the open Atlantic immediately east of the Antillean Islands are shown in three sections from north to south. Fig. 5 shows the observations made in the first part of the series entirely to the north (northeast) of the Antillean ridge (see

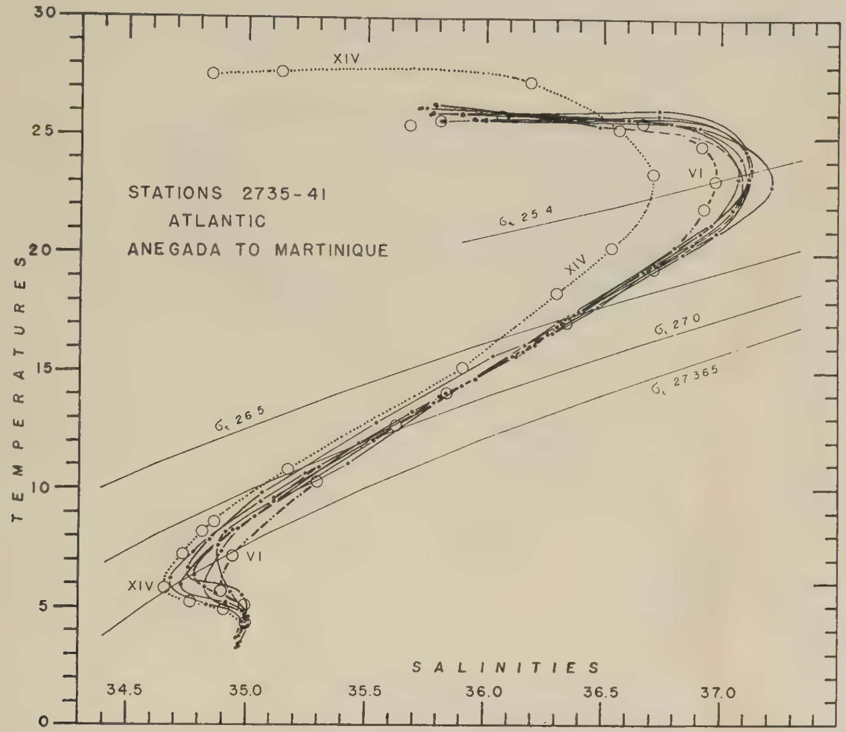


Figure 6. T–S correlations in the Atlantic along the northern half of the Lesser Antilles. See legend for fig. 5.

Fig. 1). A comparison with Jacobsen's average curves clearly shows this region to contain only waters of Jacobsen's southern Sargasso Sea type (VI) at all levels and at all stations without exception. In the next series of stations (Fig. 6), extending about half-way southward off the eastern side of the Lesser Antilles, the maximum salinity layer appears to be still of exclusively southern Sargasso Sea type, while the minimum salinity layer shows a great variety of values intermediate between those characteristic of the southern Sargasso Sea and those of the North Equatorial Current (Jacobsen's area XIV). The disappearance of the Sargasso Sea characteristics from the minimum salinity layer and from the isopycnic surface of σ_t = 27.365 is most strikingly shown in figure 20, page 24. The layers between maximum salinity and the isothermal surface of about 12° C. are also entirely of Sargasso Sea type, with only one single exception *at the northern end* (Station 2735, see also figure 18, page 22), where the characteristics are rather surprisingly of the southeastern kind (Jacobsen's

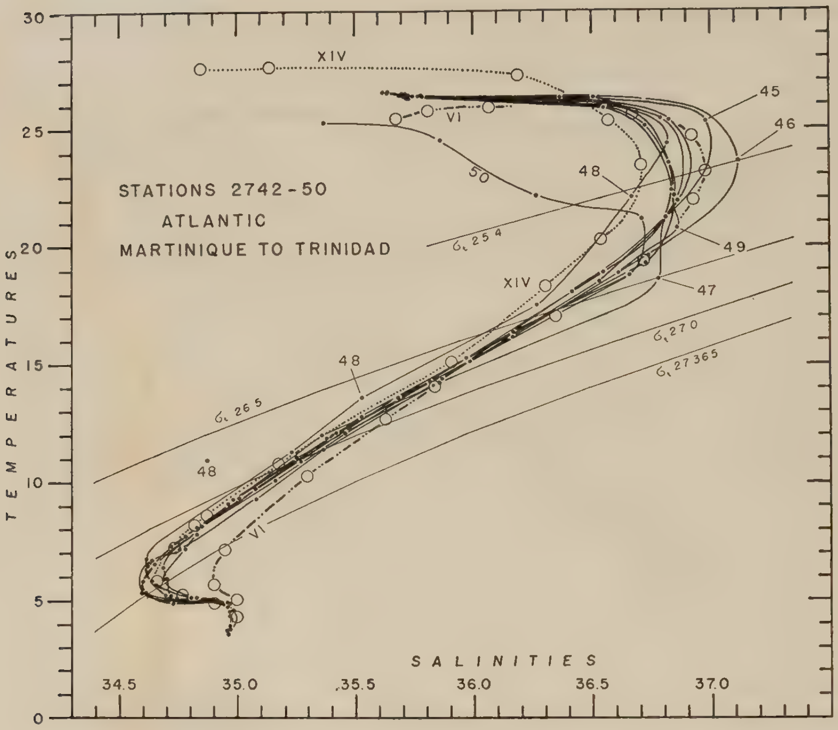


Figure 7. T–S correlations in the Atlantic along the southern half of the Lesser Antilles. See legend for fig. 5.

area XIV). There is no intrinsic evidence of errors in the determination at this station, and the deviations from neighboring stations are consistent through several depths of observation. The values have therefore been fully accepted in the plotting of the synoptic charts shown in Figs. 12–16.

In the southernmost series of observations in the Atlantic profile east of the Lesser Antilles (Fig. 7), we finally note a similar diversity of curves through intermediate values between those of the Sargasso Sea and North Equatorial type around *maximum salinities* as that which was found around minimum salinity values in the intermediate section of the Atlantic profile (Fig. 6). In the southernmost section (Fig. 7), however, the minimum salinity values are as uniformly North Equatorial as they were uniformly of Sargasso Sea type in the northernmost section (Fig. 5.)

It is thus evident that the southward penetration of maximum salinity waters of southern Sargasso Sea type above minimum salinity waters of North Equa-

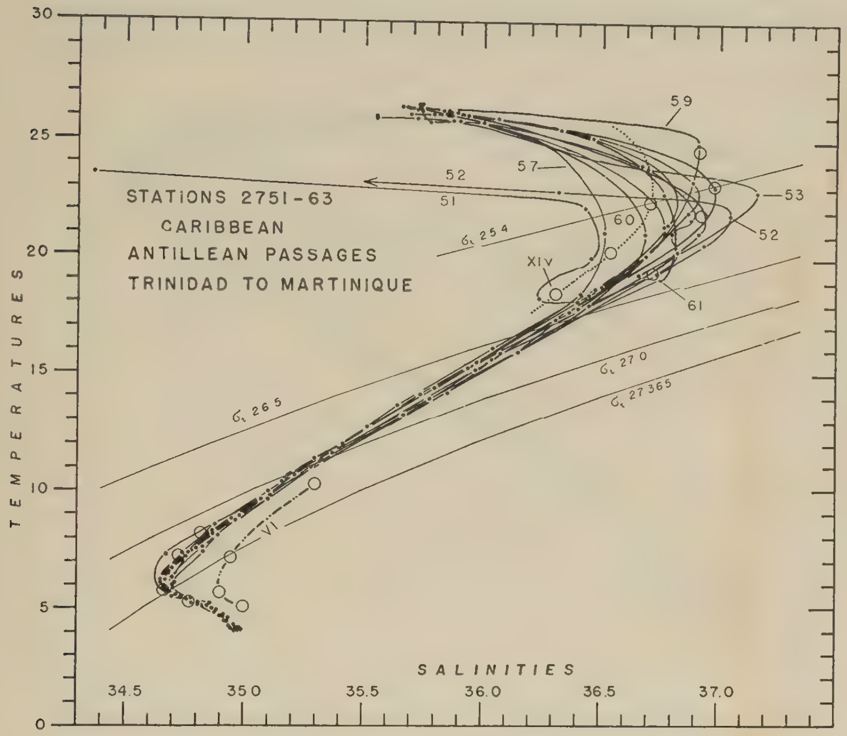


Figure 8. T–S correlations in the Caribbean along the southern half of the Lesser Antilles. See legend for fig. 5.

torial characteristics is largely accomplished even before the layers reach to the eastern entrances to the Caribbean. In fact, only a very narrow streak of maximum salinity water of the type identified by Jacobsen from area XIV seems to penetrate into the Caribbean at all, although it is still clearly observable at two of the southernmost stations in our first North–South profile through the open waters of the eastern Caribbean (Fig. 10). In a study of the further westward movement of the maximum salinity layer, however, we must also bear in mind that vertical mixing through a layer of southern Sargasso Sea type will tend to reduce its salinities and change its T–S curve towards a North Equatorial character ("compensation mixing," see p. 15), a development which has already previously been referred to (Parr 1937, p. 79, Fig. 55). On the whole, it seems indicated that the maximum salinity layer throughout the Central American basins must be mainly derived from the southern Sargasso Sea (Nielsen 1925, Parr 1937), and if this should be true, and it should also be true

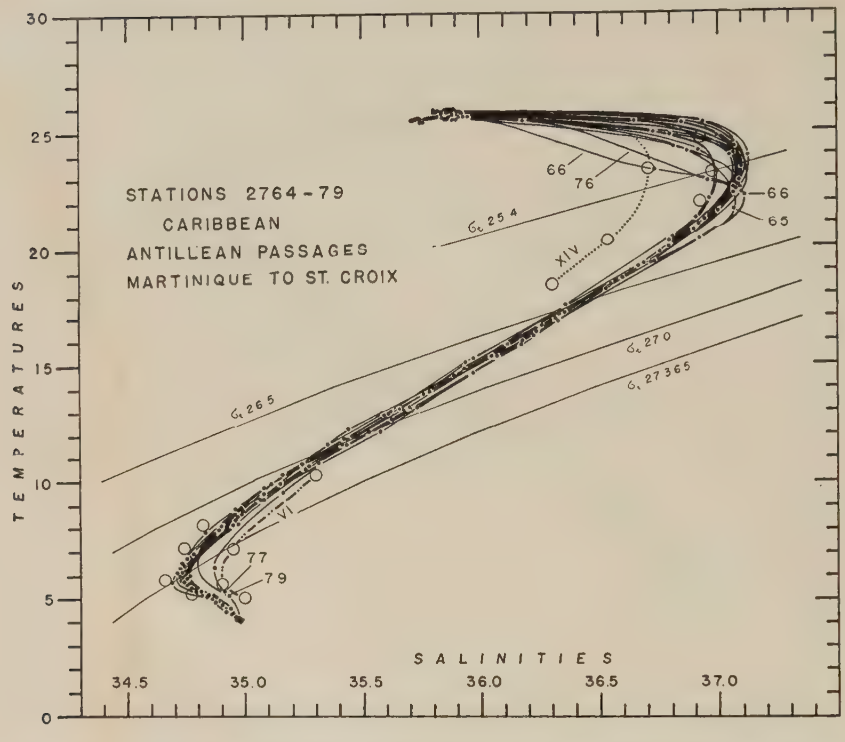


Figure 9. T–S correlations in the Caribbean along the northern half of the Lesser Antilles. See legend for fig. 5.

that the North Equatorial Current in the Atlantic is actually transporting a considerable volume of maximum salinity water of the type described by Jacobsen from area XIV, we patently have a very interesting problem in relation to the fate of the North Equatorial maximum salinity layer, which, however, is beyond the scope of the present report.

MIXING

Figs. 12–16 give the synoptic distribution of temperatures in four isopycnic surfaces, one (σ_t 25.4) corresponding very closely to the maximum salinity surface, one (σ_t 27.365) similarly located with reference to minimum salinity, and the other two representing intermediate surfaces between maximum and minimum salinity values (see density intercepts of T–S correlation curves in Figs. 5–11). The distribution pattern of maximum and minimum salinities are also

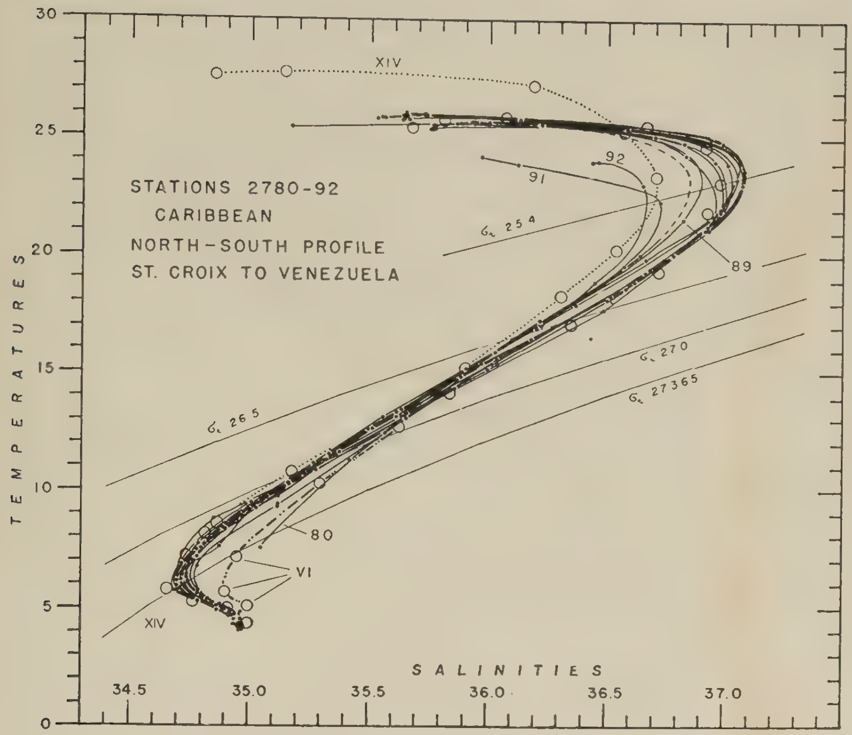


Figure 10. T–S correlations in the first N–S profile through the open Caribbean. See legend for fig. 5.

presented in Figs. 13 and 17, for comparison with Figs. 12 and 16. Isopycnic temperatures were selected in preference to isopycnic salinities for the reason that, due to the angles of intercept between the T–S correlation curves the isopycnic temperatures are less affected by uncertainties of interpolation than are the salinities, at the same time as the ratio between a unit on the temperature scale in our T–S correlation curves, and the limit of accuracy for the actual temperature determinations is ten times as great as the ratio between the salinity units and the accuracy of the salinity titrations.

From Figures 12–16, it is clear that the situation with reference to the "streakiness" of various layers was of the same general nature in 1937 as in 1933 (Parr 1937) with the streakiness relatively persistent in the intermediate layers (σ_t 26.5 and σ_t 27.0), while it rapidly disappeared into a comparatively uniform north-south gradient in the maximum and minimum salinity layers and in the

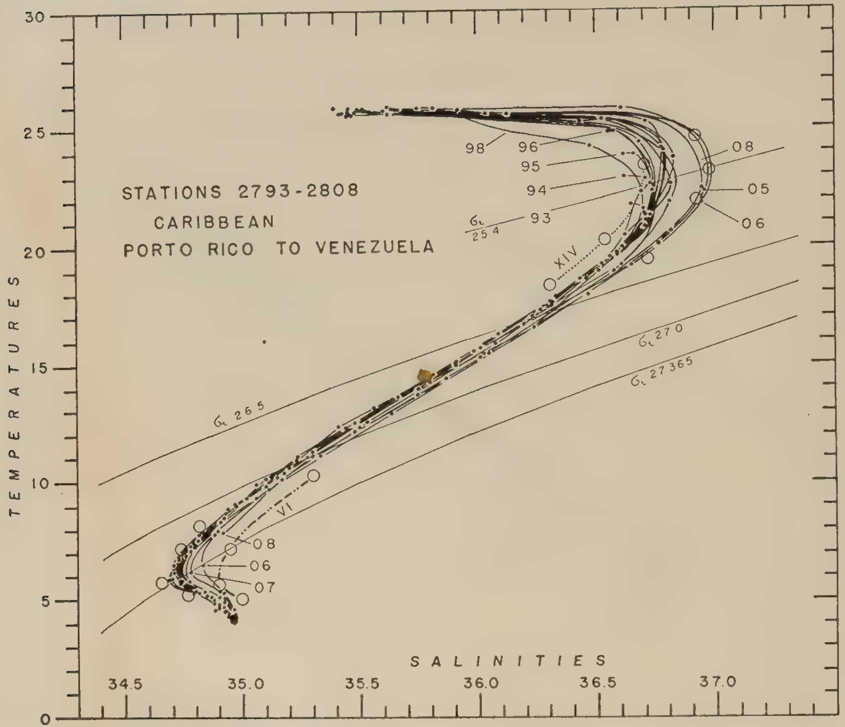


Figure 11. T–S correlations in the second N–S profile through the open Caribbean. See legend for fig. 5.

corresponding isopycnic surfaces of σ_t 25.4 and σ_t 27.365. This is perhaps even more strikingly evident in a comparison of the transverse isopycnic temperature curves given in Figures 18–20. In the 1937 observations, however, we are able to extend our comparisons beyond the Antillean Islands to the eastward, and by so doing we find that the streakiness with which the salinity minimum layer and the isopycnic surface of σ_t 27.365 arrive off the eastern side of the Antilles is almost obliterated in the passage between the Antillean Islands (see Figures 16 and 17). In this passage the streakiness, or transverse variability, in the maximum salinity layer and in the isopycnic surface of σ_t 25.4 is also greatly reduced, although not nearly obliterated (Figures 12 and 13), while the reduction in the streakiness and transverse range of variation in the intermediate isopycnic surfaces of σ_t 26.5 and σ_t 27.0 is relatively slight (compare the curve for Stations 2735–50 with Stations 2780–51, Figs. 18–19). It thus seems indicated that factors coming into play in the passage of the water between the Antillean

Islands have induced a greater amount of mixing in the isopycnic surfaces around maximum and minimum salinity values, than in the isopycnic surfaces between. One might immediately suggest a relationship to the great vertical stability around maximum salinity, and to the relative proximity to the topographic complications of the bottom around minimum salinity. But first it will be necessary to consider to what extent the reduction of streakiness might be due to vertical, instead of lateral, mixing alone. In this connection a serious objection to the previous use of the example of the maximum and minimum salinity layers in the eastern Caribbean as a possible illustration of the relationship between vertical mixing and horizontal stability (Parr 1936) has since occurred to the writer. Since the isopycnic surfaces of σ_t 26.5 and σ_t 27.0, both intercept virtually straight portions of the T–S curves (Figs. 5–11), it is evident that a change in the distribution of identifying properties in these isopycnic surfaces can only be due to lateral and not in a significant degree to vertical mixing (Parr 1938). To the extent that the streakiness of these intermediate isopycnic surfaces has been reduced by the passage between the Antillean Islands, the phenomenon may therefore be ascribed to lateral mixing. But in the isopycnic surfaces around maximum and minimum salinities the identifying properties involved in the determination of density (temperatures and salinities) may both be very significantly changed by vertical mixing alone. Since furthermore the rate of change in either identifying property per unit vertical mixing (that is, per unit vertical exchange of volume) at an inflection point in the vertical distribution curve for one of the properties affecting density, will decrease as the vertical mixing progresses and the radius of curvature of the vertical distribution curve increases, we may have a downstream "mixing compensation," quite comparable with the biological phenomenon of "compensation growth" as interpreted by Hodgson (1929). Assuming a uniform intensity of vertical mixing throughout, the cumulative curve of change in identifying properties around a maximum or minimum value in the course of the downstream movement would thus take a form similar to that of the curves shown in Fig. 21, p. 24 (modified from Hodgson's illustration in explanation of compensation growth). If the difference between laterally adjacent streaks (A_1, B_1, C_1 in profile 1, Fig. 21) is mainly one of more or less advanced or deferred vertical mixing, it is evident from our figure, in which the three curves are identical, that there will be a gradual obliteration downstream of the differences between the lateral streaks, even in the complete absence of lateral mixing and with a uniform vertical mixing in all streaks. For this reason the choice of maximum and minimum salinity layers or corresponding isopycnic surfaces for a comparison with isopycnic surfaces intercepting straight portions of the T-S curve in illustration of the possible relationship between vertical stability and horizontal mixing was obviously an unfortunate one which has to be discarded.

(*Turn to page 22*)

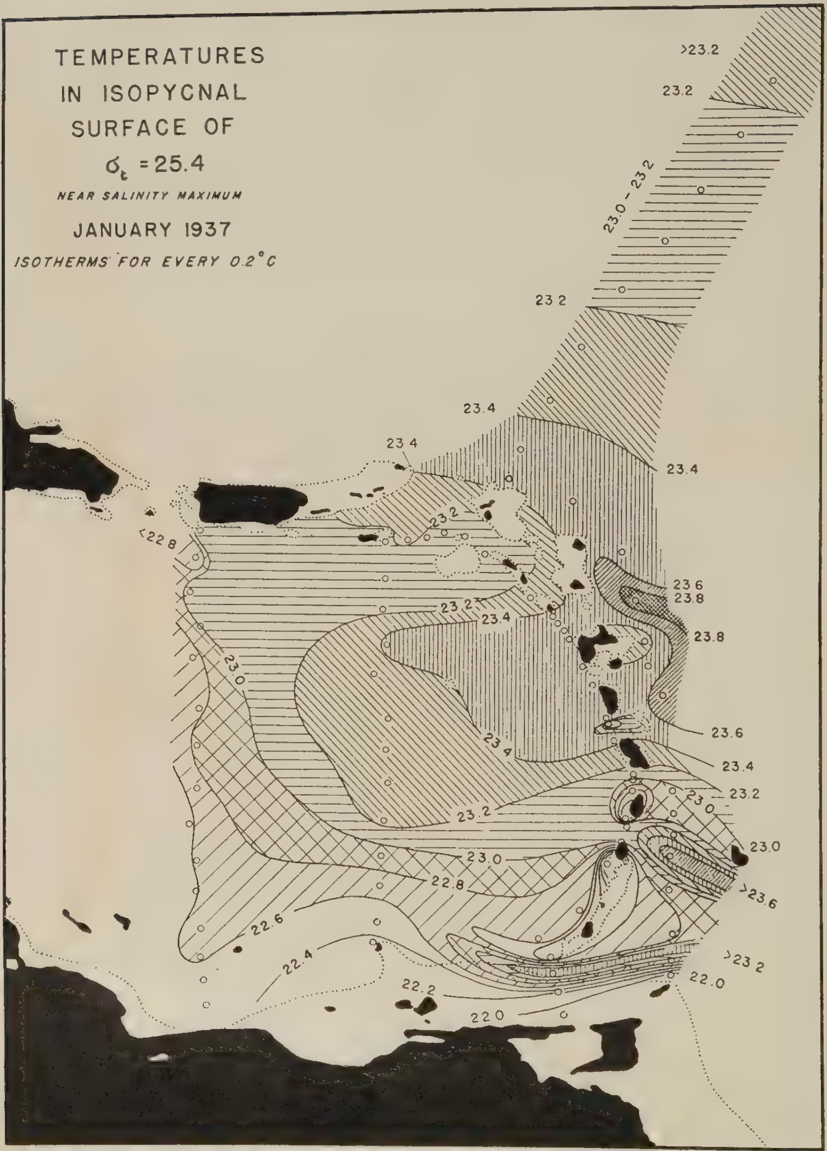

TEMPERATURES
IN ISOPYCNAL
SURFACE OF
σ_t = 25.4
NEAR SALINITY MAXIMUM
JANUARY 1937
ISOTHERMS FOR EVERY 0.2°C
>23.2
23.2
23.0 – 23.2
23.2
23.4
23.4
23.4
<22.8
23.2
23.2
23.4
23.6
23.8
23.8
23.0
23.4
23.6
23.4
23.2
23.0
23.2
23.0
23.0
22.8
>23.6
22.6
22.4
>23.2
22.0
22.2
22.0

Figure 12. Synoptic chart of temperature distribution in isopycnic surface of σ_t = 25.4, near salinity maximum. Isotherms for every .2°C.

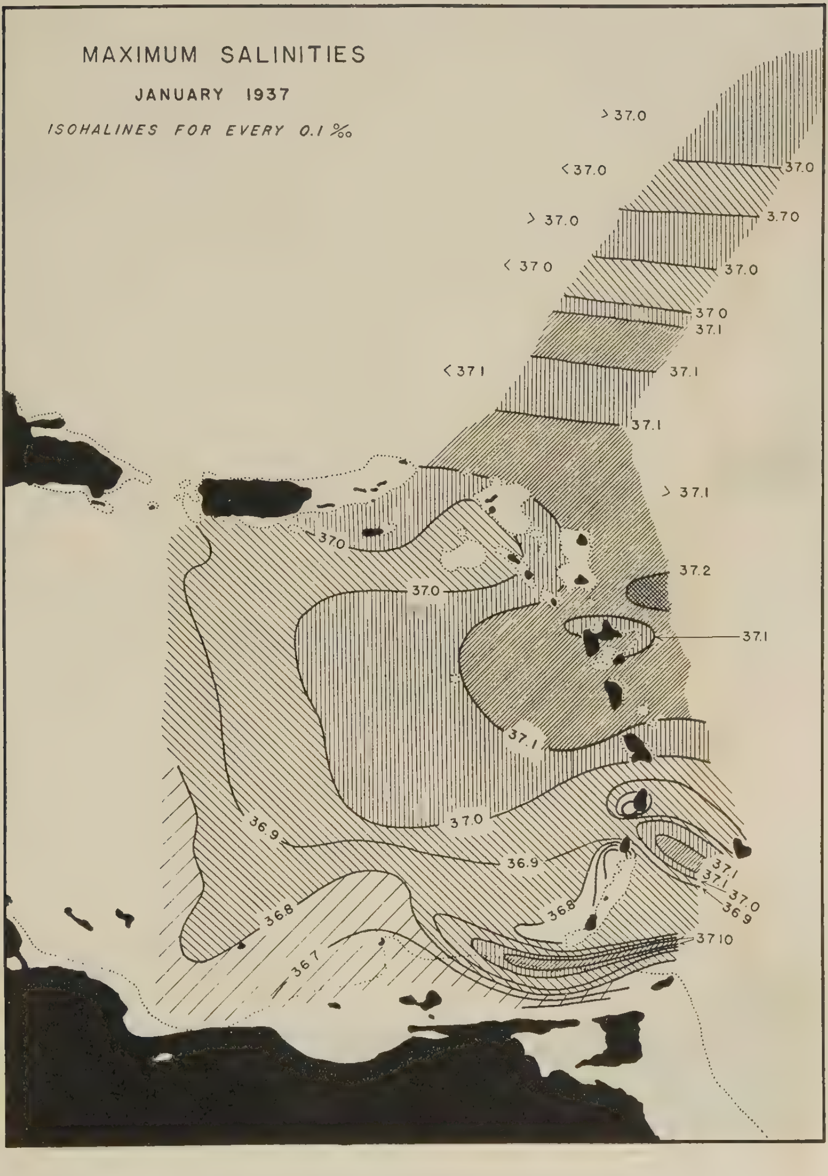

MAXIMUM SALINITIES
JANUARY 1937
ISOHALINES FOR EVERY 0.1 ‰
> 37.0
< 37.0
> 37.0
< 37.0
37.0
3.70
37.0
37.0
37.1
37.1
< 37.1
37.1
> 37.1
37.0
37.2
37.0
37.1
37.1
37.0
36.9
36.9
36.8
36.8
36.7
37.1
37.1
37.0
36.9
37.10

Figure 13. Synoptic chart of temperature distribution in isopycnic surface of $\sigma_t = 27.365$, near salinity minimum. Isotherms for every .1°C.

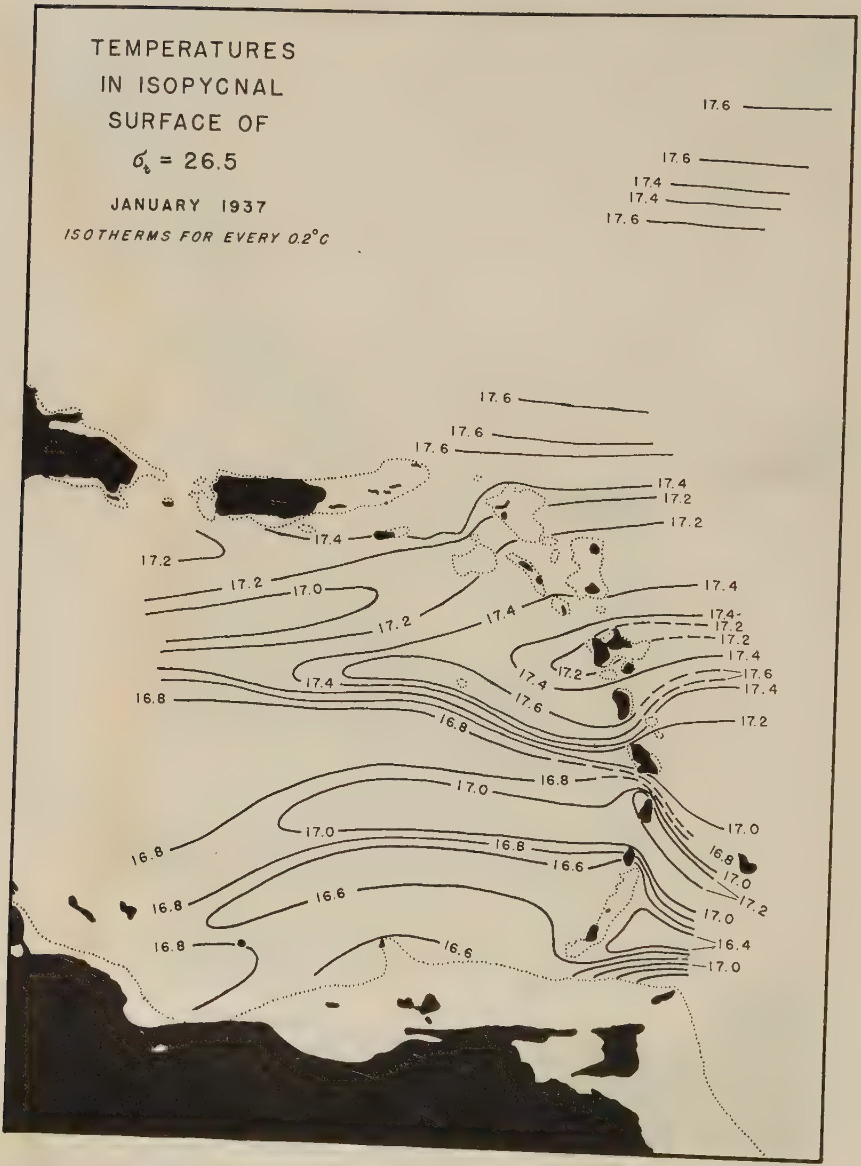

TEMPERATURES
IN ISOPYCNAL
SURFACE OF
σt = 26.5
JANUARY 1937
ISOTHERMS FOR EVERY 0.2°C
17.6
17.6
17.4
17.4
17.6
17.6
17.6
17.6
17.4
17.2
17.2
17.4
17.2
17.2
17.0
17.4
17.2
17.4
17.4-
17.2
17.2
17.4
17.2
17.6
17.4
17.4
17.6
17.4
17.2
16.8
16.8
17.0
16.8
17.0
17.0
16.8
16.8
16.6
16.8
16.8
17.0
16.6
17.2
17.0
16.8
16.6
16.4
17.0

Figure 14. Synoptic chart of temperature distribution in isopycnic surface of σ_t = 26.5. Isotherms for every .2°C.

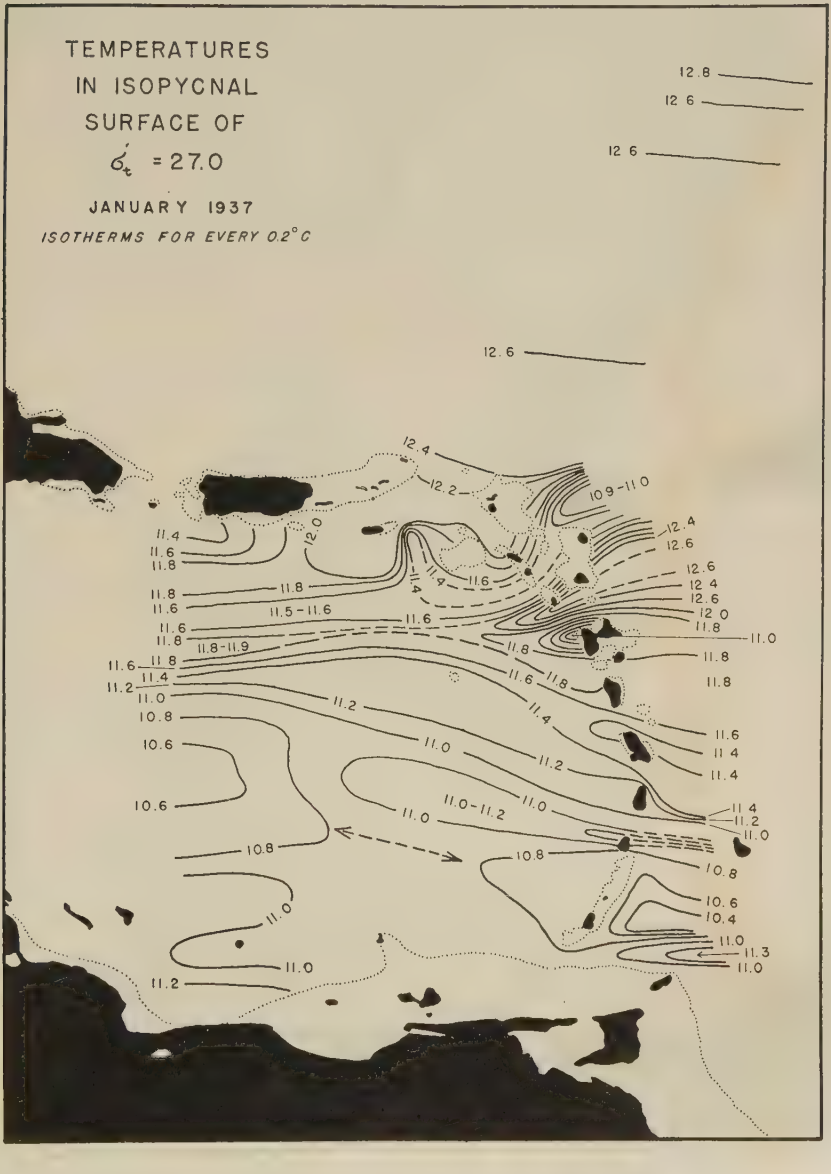

TEMPERATURES
IN ISOPYCNAL
SURFACE OF
σt = 27.0
JANUARY 1937
ISOTHERMS FOR EVERY 0.2°C
12.8
12 6
12 6
12. 6
12.4
12.2
10.9-11.0
12.4
12.6
12.6
12 4
12.6
12 0
11.8
11.0
11.8
11.8
11.4
11.6
11.8
12.0
11.8
11.6
11.8
11.4
11.6
11.5-11.6
11.6
11.6
11.8
11.8-11.9
11.8
11.6
11 8
11.4
11.2
11.0
11.6
11.8
11.2
10.8
11.4
11.6
11 4
11.4
10.6
11.0
11.2
10.6
11.0-11.2
11.0
11 4
11.2
11.0
11.0
10.8
10.8
10.8
10.6
10.4
11.0
11.0
11.3
11.0
11.2

Figure 15. Synoptic chart of temperature distribution in isopycnic surface of $\sigma_t = 27.0$. Isotherms for every .2°C.

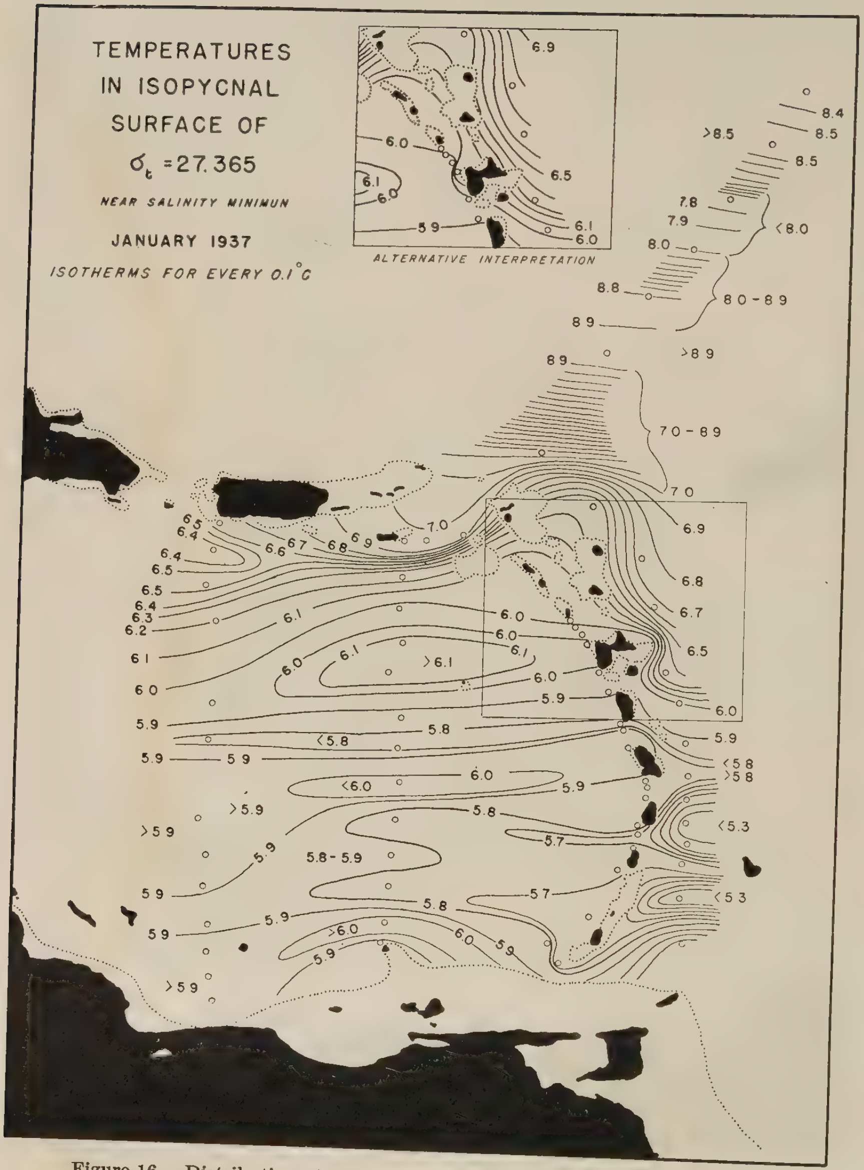

TEMPERATURES
IN ISOPYCNAL
SURFACE OF
σ_t = 27.365
NEAR SALINITY MINIMUM
JANUARY 1937
ISOTHERMS FOR EVERY 0.1°C
ALTERNATIVE INTERPRETATION
6.9
6.0
6.1
6.5
5.9
>8.5
8.4
8.5
7.8
7.9
<8.0
8.0
8.8
8 0 - 8 9
8 9
>8 9
7 0 - 8 9
7 0
7.0
6.8
6.7
6.6
6.4
6.3
6.2
6 1
6 0
>6.1
5.9
5.8
<5.8
<6.0
>5.9
5.8 - 5.9
5.7
>5 8
<5.3
<5 3
>6.0
>5 9

Figure 16. Distribution of maximum salinities. Isohalines for every .1°/₀₀.

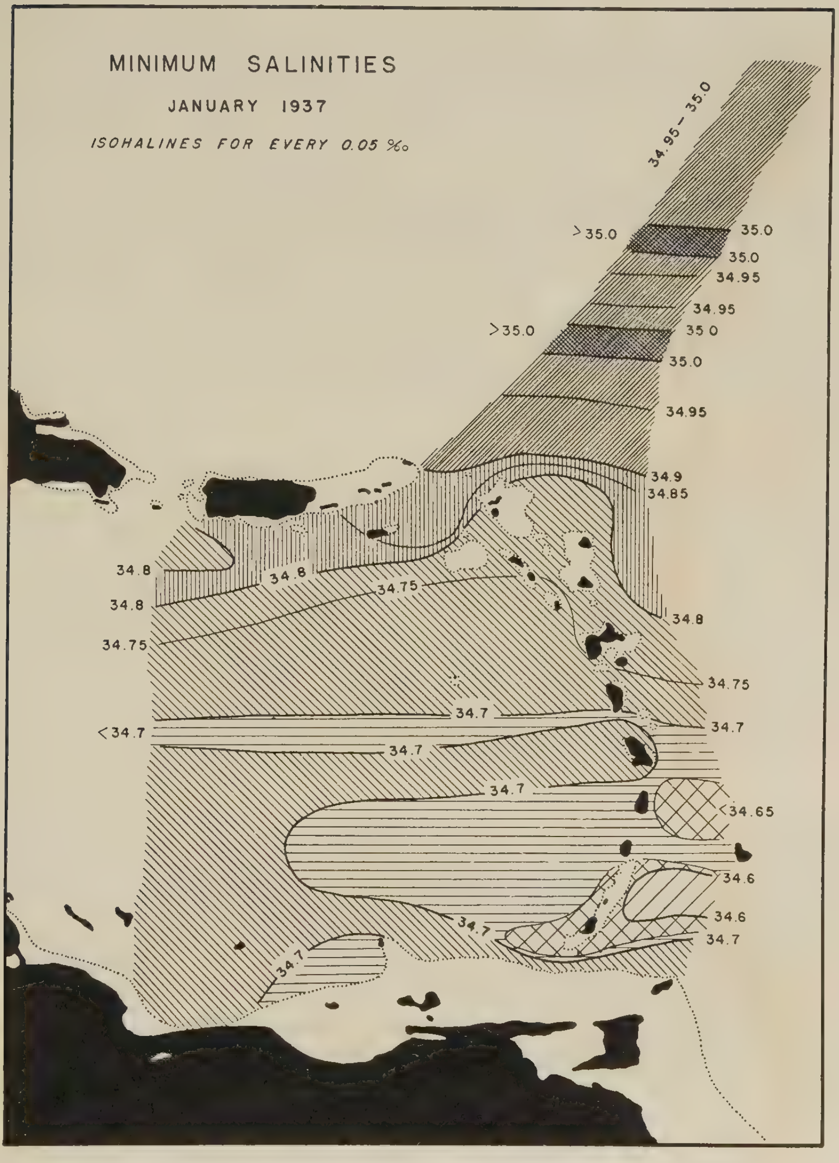

MINIMUM SALINITIES
JANUARY 1937
ISOHALINES FOR EVERY 0.05 ‰
34.95 – 35.0
>35.0
35.0
35.0
34.95
34.95
>35.0
35.0
35.0
34.95
34.9
34.85
34.8
34.8
34.8
34.75
34.75
34.8
34.75
34.7
<34.7
34.7
34.7
34.7
<34.65
34.6
34.6
34.7
34.7
34.7

Figure 17. Distribution of minimum salinities. Isohalines for every .05°/₀₀.

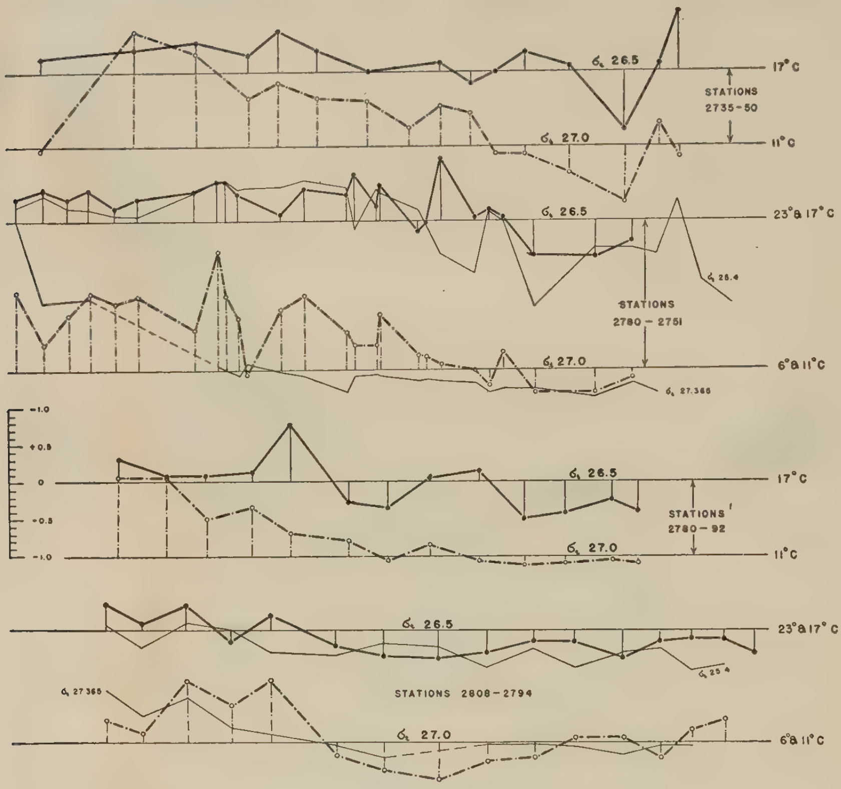


Figure 18. Transverse temperature profiles for isopycnic surfaces of σ_t 26.5 (solid heavy line), and 27.0 (heavy dot and dash), with profiles for σ_t 25.4 and 27.386 (light solid line) entered for comparison in the first and last series inside of the Caribbean. Upper series (St. 2735–50) from the Atlantic along the Lesser Antilles. Second series from the Caribbean along the Lesser Antilles immediately inside of the passages. Last two series through the open Caribbean. Datum lines refer to 23°C. for σ_t 25.4; 17°C. for σ_t 26.5; 11°C. for σ_t 27.0; and 6°C. for σ_t 27.365. Scale of deviations in °C. at middle left.

To avoid the confusing aspect of mixing compensation just discussed, one might attempt to make comparisons between different isopycnic surfaces within the straight portion of the T–S curve, such as the surfaces of σ_t 26.5 and σ_t 27.0 for which synoptic charts are given in Figs. 14 and 15. But in so doing we would be reduced to a consideration of quantitative instead of simple qualitative differences in the synoptic patterns, requiring an accuracy of observations and a precise evaluation of all factors involved which can certainly not be obtained from a system of stations as widely spaced as those here reported upon. The

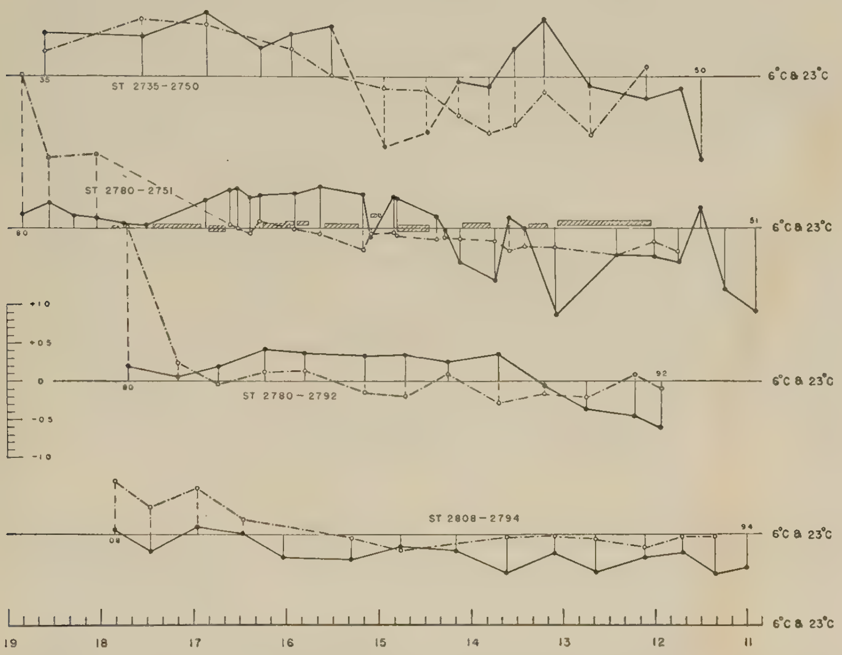


Figure 19. Transverse temperature curves for isopycnic surfaces of σ_t = 25.4 (near salinity maximum) and σ_t = 27.365 (near salinity minimum). Upper series in the Atlantic along Lesser Antilles. Second series in Caribbean immediately inside of Lesser Antilles, with positions of Islands indicated by hatched blocks. Lower two series through open Caribbean. Datum lines refer to 23°C. for 25.4 and 6°C. for σ_t 27.365. Scale of deviations in °C. at left. Degrees lattitude at bottom (does not apply to the last stations at the left in the second series, see station chart on page 2).

factor of lateral shearing stresses, which would be a function of lateral variations in longitudinal velocities, and is of an importance equal to that of vertical stability, would have to be determined with an accuracy which the present uncertainties in the practical applications of the velocity equation, caused among other things by the guesswork involved in selection of a datum surface, would certainly not permit. Average vertical stabilities would also have to be evaluated in accurate figures along isopycnic surfaces *in proportion* to the lateral variations in velocities along the same surfaces, which, as we have just mentioned, can hardly themselves be accurately determined. What seemed of interest and possible significance in the comparison between the distribution patterns of various layers in the Eastern Caribbean, was therefore not to be found in precise quantitative estimates, but in the fact that qualitative differences in these patterns would appear to be associated with a close proximity to positive deviations in vertical stability. The integration of the effects of

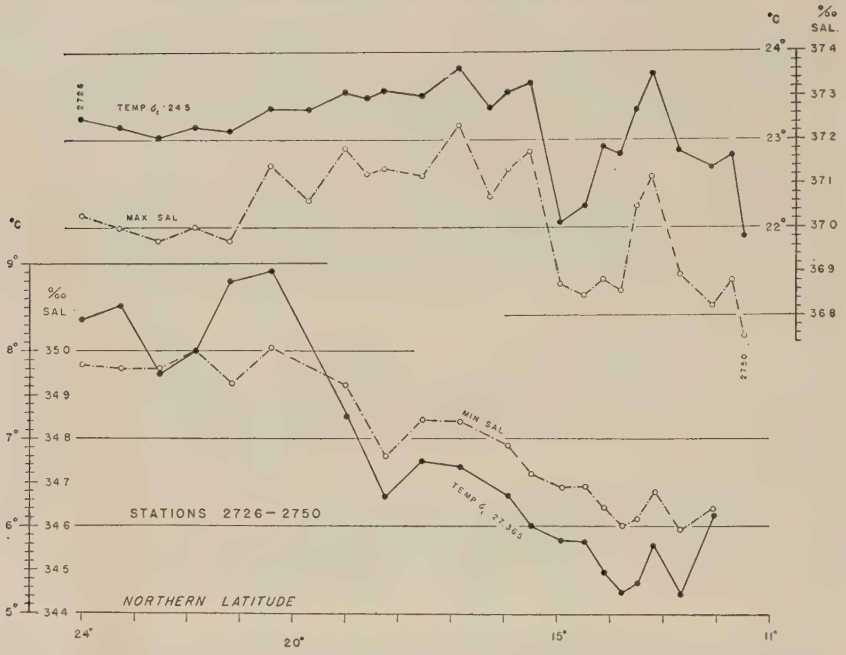


Figure 20. Profiles of maximum and minimum salinities (open circles, dot and dash) and of temperatures (solid lines, black dots) in the isopycnic surfaces of σ_t 27.365 for entire Atlantic profile. Latitude in °N. at bottom.

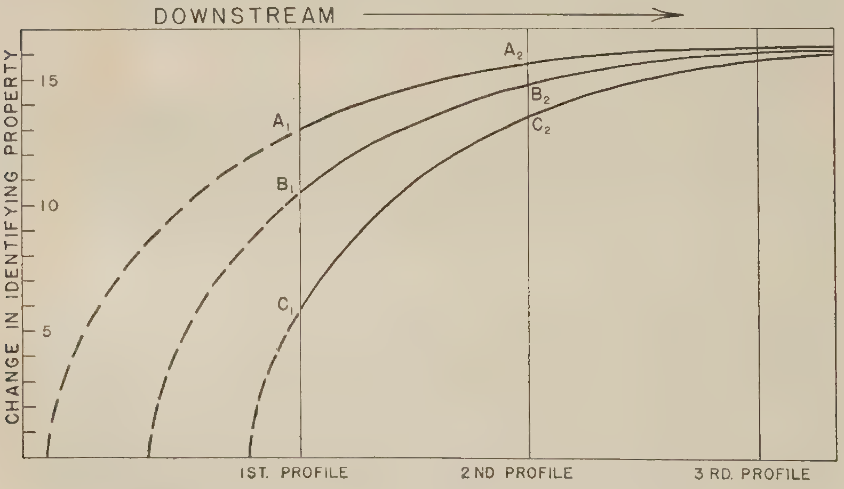


Figure 21. Vertical mixing compensation. See text, page 15.

generally decreasing vertical stability, and undoubtedly also decreasing lateral shearing stresses towards the depths did apparently not result in a uniformly decreasing curve of lateral mixing, but on the contrary, gave indication of two separate maxima of such mixing each closely associated with a major or a minor positive deviation from the general trend of decreasing vertical stability (see Figs. 22–23).

It has been stated by Dietrich (1937) that there is no vertical stability maximum around minimum salinity values. Although the wide vertical spacing of observations (100–200 meters apart) in these depths make precise determination of the form of the density curves through the layers concerned a virtual impossibility, it is nevertheless by various methods quite possible to show that an actual increase in vertical stability must occur in, or very near to, the minimum salinity surface. From a consideration of the derivation of the σ_t values alone, the probability of this occurrence is immediately indicated. By standard methods the value of σ_t is determined by the empirical equation:

$$\sigma_t = \sigma_o - D$$

With the value of D steadily decreasing towards the depths, with decreasing temperatures, and the value for σ_o first decreasing towards the salinity minimum and then increasing again towards greater depths, it is evident that if this change from a negative to a positive rate of change of σ_o around salinity minimum should not find expression in a secondary increase in the vertical gradient of σ_t at and below salinity minimum, there would have to be a corresponding and compensating irregularity in the vertical temperature gradient of which there is no general indication in the data. An actual case (from 1937) is shown in Fig. 22. It is evident from the form of the vertical curves for D and σ_o that the increase in vertical stability should normally be expected to begin slightly above the salinity minimum and reach its maximum somewhat below. If we choose the apparent (interpolated) depth of minimum salinity at each station as our zero level and plot the observed densities according to their height above or depth below this level, we also find that there is, on the average, a definite inflection in the vertical density curves around or immediately below salinity minimum, both in the 1933 and in the 1937 observations from the Eastern Caribbean.

Since the salinity minimum values, and therefore also the distribution pattern of the salinity minimum surface, according to the manner in which the vertical curves are drawn and read, must necessarily also be indicative and indirectly representative of salinities and salinity distributions immediately below, it seems entirely proper to claim association between the salinity minimum distribution pattern and the secondary vertical stability maximum. Finally, it should perhaps also be mentioned at this point that the principle that vertical stability and horizontal mixing should be in direct relationship to

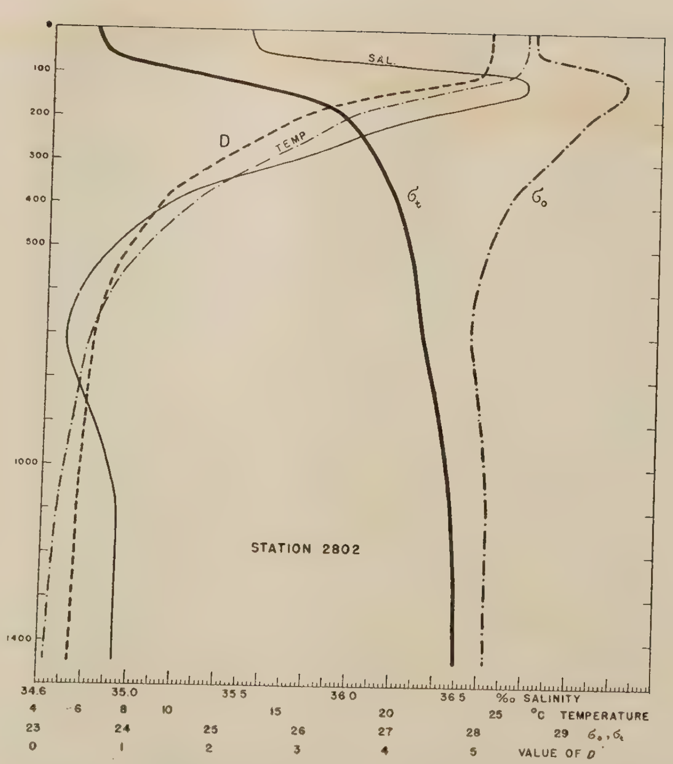


Figure 22. Vertical density curve (σ_t) for station 2802 (Atlantis 1937) and its derivation from vertical curves for salinity (Sal.), temperature (Temp.), σ_o and *D*.

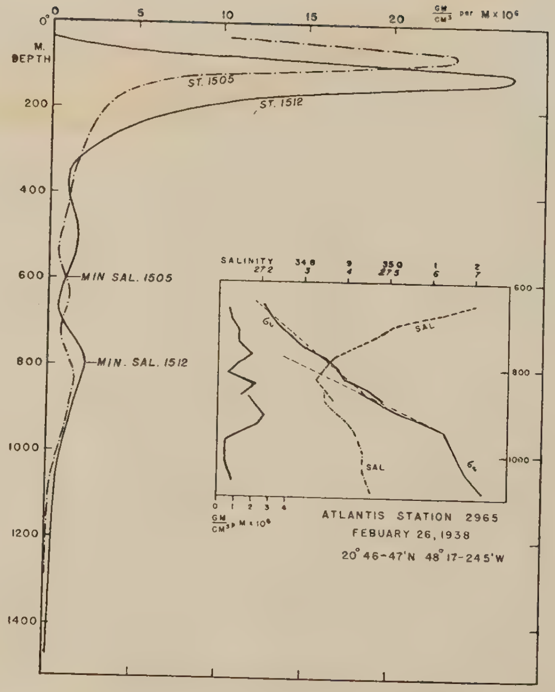


Figure 23. Curves of $\frac{\Delta\sigma_t}{\Delta h}$ for stations 1505 and 1512 (Atlantis 1933). See text. *Insert:* Curves of salinities, σ_t, and approximate curve of vertical stability at "Atlantis" station 2965. See page 27. Observations made in 2 overlapping series.

each other does not require any vertical stability *in* the layer in which lateral mixing occurs, but merely that this layer should be in fairly close *contact* with *one* or confined *between* two vertically stable boundaries.

With regard to the actual values of the secondary vertical stability maximum, it is evident that the great vertical distance between observations makes it impossible to arrive at accurate figures and also that the increase in the vertical density gradient and accordingly also in the vertical stability curve must be minimized in proportion to this distance between observations. Therefore, if the transverse isopycnals around salinity minimum were forming a parallel system, we would be entitled to regard the *maximum estimated* vertical stability around salinity minimum as a *minimum* value for the *actual* stability of this layer. And it was noted in the 1933 observations that there seemed to be a tendency for the more closely spaced observations around salinity minimum to show greater vertical stability values in the secondary maximum. The $\frac{\Delta\sigma_t}{\Delta h}$ curves for the two stations in the transverse profile on which the previously used average T–S curve was based (Parr 1930, Fig. 3; 1937, Fig. 45) at which observations were most closely spaced around salinity minimum are given in Fig. 23. At Station 1512 the observations were more closely spaced in these depths (only 51 meters apart around salinity minimum) than at any other station made in the Eastern Caribbean, and this station also showed the highest estimated vertical stability value in the secondary stability maximum. Unfortunately the premise that the transverse isopycnals should run parallel around salinity minimum does not hold true. Although the maximum estimated vertical stability can therefore not a priori be used as a minimum value for all actual values in nature, the probability remains that the *maximum actual* vertical stability in the secondary maximum must be *greater* than the *maximum estimated* from our discontinuous observations.

During the 1938 cruise to the Central American Seas, a special set of observations was made by the "Atlantis" in the Cayman Sea just south of Cuba, with the instruments more closely spaced (only 25 meters apart) in the depths around the salinity minimum. The records of these observations have just come to hand and are presented in the insert in figure 23, which again confirms the existence of an increased vertical stability in and immediately below the minimum salinity layer. At Station 2965 the average for the first 121 meters below salinity minimum ($2.1 \frac{\text{GM}}{\text{CM}^3}$ pr. M.10^6) is nearly twice the average (1.1) for the first 175 meters above. It should also be kept in mind that Station 2965 is located in a region with relatively high minimum salinity values (34.83°/₀₀) and great thickness of the layers (right side of current) in which the increase in vertical stability associated with the increase in salinities below must therefore be considerably less than the average for the Central American Seas.

On the basis of the preceding, it therefore definitely seems valid to repeat that the peculiarities of the salinity distribution in the maximum and minimum salinity layers, and in corresponding isopycnic surfaces, as compared with the synoptic patterns of the intermediate isopycnals (particularly when we consider σ_t 27.0) is clearly associated with positive deviations from the general trend of decreasing vertical stability. Since, however, the possibility of a mixing compensation already discussed on page 15 introduces a further complication not previously taken into consideration, it nevertheless seems advisable to give up the attempt to extract definitive evidence from a case as complicated as that of the Eastern Caribbean, and to withdraw this previously used illustration of a possible application of the principle concerning the relationship between vertical stability and lateral mixing from further consideration until much more precise information may become available. In so doing, however, the author wishes to emphasize the fact that this withdrawal of an ambiguous, but definitely not contradictory, illustration in no manner affects his confidence in the previously enunciated principle, for which unequivocal evidence is probably more easily obtainable by meteorological research and experimental investigations of liquid dynamics for which apparatus is now under construction.

SUMMARY

The 1933 records from the Eastern Caribbean showed a very great discrepancy with previous observations from adjacent parts of the open Atlantic, with reference to salinities in the surface layer. In the 1937 observations herein reported upon, this discrepancy is greatly reduced and considerable variations in Caribbean surface salinities are thus indicated.

With reference to the deeper layers, the 1937 data confirm the findings of 1933 previously reported upon (Parr 1937). It seems indicated that the intrusion of a maximum salinity layer of Southern Sargasso Sea origin between surface and minimum salinity layers mainly derived from the North Equatorial Current (Nielsen 1925, Parr 1937) is largely completed before the water masses enter the Eastern Caribbean.

Synoptic temperature charts are given for four isopycnic surfaces, one corresponding very closely to the maximum salinity surface, another to the minimum salinity layer and the remaining two to intermediate layers between these.

With reference to "streakiness" these synoptic charts give general confirmation of the comparison previously made between the distributions of maximum and minimum salinities and salinities in the isothermal surface of 15°C. The possibility of an elimination of streakiness by compensating cumulative effects of simple vertical mixing is brought out, and in view of the uncertainties introduced by this factor, which has not previously been taken into consideration, it is considered advisable to disregard all comparisons between layers identified

with inflection points on the T–S correlation and to resort to meteorological and experimental hydrodynamic methods instead for the further study of the relationship between vertical stability and lateral mixing.

LITERATURE REFERRED TO

DIETRICH, G.:

1937. Review of A. E. Parr, 1937 (below) in Journal du Conseil. Vol. XII, No. 3, pp. 341–42. Copenhagen, 1937.

HODGSON, W. C.:

1929. Investigations into the Age, Length and Maturity of the Herring of the Southern North Sea. Pt. III. Fishery Inv. Ministry Agric. Fish. Ser. II, Vol. XI, No. 7. London, 1929.

JACOBSEN, T. P.:

1929. Contribution to the hydrography of the North Atlantic. Danish "Dana" Exp. 1920–22. Oceanogr. Rep. No. 3. Copenhagen, 1929.

NIELSEN, T. N.:

1925. Golfströmmen. Geografisk Tidskrift. Bind 28, Hefte 1. Copenhagen, 1925.

PARR, A. E.:

1936. On the probable relationship between vertical stability and lateral mixing processes. Journal du Conseil, Vol. XI, No. 3. Copenhagen, 1936.

1937. A contribution to the hydrography of the Caribbean and Cayman Seas. Bull. Bingham Oceanogr. Coll., Vol. V, Art. 4. New Haven, 1937.

Contribution No. 180

(*Reprinted from Transactions of the American Geophysical Union,*
Nineteenth Annual Meeting, 1938)

A PROMISING THEORY CONCERNING THE CAUSES AND RESULTS OF LONG-PERIOD VARIATIONS IN THE STRENGTH OF THE GULF STREAM SYSTEM

C. O'D. Iselin

(Contribution No. 180 of the Woods Hole Oceanographic Institution)

A year ago I outlined [Iselin, 1937] the new cooperative investigation that is being conducted by the Woods Hole Oceanographic Institution and the Bermuda Biological Station. This investigation has as its ultimate goal the solution of the problem of whether or not gradual changes in the strength of the Gulf Stream System have any bearing on the climate and fishery of Great Britain. In an article soon to appear in "Nature" the program of observations that will be carried out during the 5-year period for which funds are available has been discussed more fully. However, one suggestion contained in that report is perhaps worthy of further treatment at the present time.

Assuming that the North Atlantic Eddy on the whole fluctuates in strength from year to year by a significant amount, are any of the existing theories capable of pointing to the causes and the most important results of such variations? This question had to be carefully considered before working out a program of observations that might be expected to yield satisfactory results. In the light of modern oceanographic knowledge no existing theory seemed entirely adequate. However, as will be discussed below, it was possible to work out a compromise theory that at present seems promising enough to justify the proposed 5-year program of work at sea.

Most investigators are agreed that the energy of the Gulf Stream System is absorbed in low latitudes from the trade-winds. Now there is little convincing data to show whether or not the trade-winds in the Atlantic do on the whole vary in strength from year to year. All that can be said is that it seems probable that the variations are quite small. Therefore, if it is assumed that the energy imparted to the water is proportional to the strength of the winds, it is difficult to see how any significant fluctuations will result in the current-system.

However, some recent studies of Professor C.-G. Rossby have pointed to a mechanism whereby relatively small changes in the strength of the wind-system over the North Atlantic might cause marked fluctuations in the volume of the currents. He has advanced evidence that there exists a critical wind-velocity below which the air slips easily over the surface of the water. But once the sea-surface has reached a certain roughness, eddies are set up in the lowest layer of the atmosphere and the coefficient of friction suddenly greatly increases. If this can be established by suitable observations at sea and if it is found that the critical velocity falls within the range of the variations in strength of the trade-winds, then it is clear how the current-system can absorb very much greater amounts of energy in years when the winds are only slightly stronger than average.

The available rather unsatisfactory evidence [Montgomery 1938] indicates that the Gulf Stream has a seasonal variation in strength that results in January and July in an increase in volume of roughly 15 per cent over the minimum values of April and October. But it remains to be established whether or not there exists annual variations of the same order of magnitude. On the whole, however, in view of Rossby's theory mentioned above it seems worth while to look for significant annual changes in the strength of the North Atlantic Eddy.

In the case of the continental slope of North America between the Florida Straits and the Grand Banks, the influence of long-period variations in the Gulf Stream seems relatively straightforward and direct. As the current decreases in strength, bottom-temperatures in the depths occupied by the main thermocline layer will rise and vice versa. During a single year, for example, north of the current off Chesapeake Bay the average depth of the 8° isotherm is known [Iselin, 1936] to have fluctuated by as much as 70 meters. Concerning these effects at mid-depth of changes in volume of the Gulf Stream there can be little doubt, provided it is admitted that the current approximately follows the principals embodied in the circulation theorem of Bjerknes. But it is the possible effects nearer the surface of changes in strength of the North Atlantic Anticyclonic Eddy as a whole that I wish to call attention to.

Assuming that in the North Atlantic we have essentially an eddy, narrow and intense on the west side and broad and weak on the east side, and assuming that the northern off-shoot from this eddy, which brings Atlantic water to the Norwegian Sea and the Labrador Sea, is relatively shallow and that it resembles a warm tongue rather than a current that behaves in the classical dynamic sense, then it can be argued that the shallow northern branches will fluctuate greatly in strength in response to relatively slight changes in the intensity of the main eddy. These assumptions do not seem unreasonable in view of what is known about the distribution of temperature and salinity in the northeastern North Atlantic. The deeper waters, carried eastward by the continuations of the Gulf Stream, appear to cross the mid-ocean ridge north of the Azores and then curving southward to be absorbed into the beginning of the Northern Equatorial Current, while near the surface a shallow relatively warm tongue seems to advance towards the northeast more or less as pictured in LeDanois' transgression-theory.

Now if the main North Atlantic Eddy should on the whole increase in strength, the circulation-theorem tells us that the dynamic height at the center of rotation must increase, which is only another way of saying that the superficial, warm-water layer must increase in thickness. Unless the volume of warm water is at the same time increased, then the eddy must decrease in diameter.

On the other hand, if the strength of the eddy should decrease, then the dynamic height at its center must fall and either the eddy must increase in diameter or some of the warm superficial water of the central region must be discharged beyond the limits of the deep, circular current-system. Because it seems probable that the volume of warm water at the center of the North Atlantic Eddy does not fluctuate much and since the size to which the Eddy can expand is restricted by the shape of the ocean-basin, it is possible that with a decreasing current-system warm water in large amounts will be discharged to the north. It can be argued that this mechanism will cause very marked fluctuations in the warm northern branches which have been thought to originate from the Gulf Stream, but the relationship is exactly the reverse from that popularly accepted. Under this theory the discharge of warm water to the north will increase when the Gulf Stream and the North Atlantic Eddy are diminishing in strength and not when they are increasing in transport. It should be added that this is also the correct relationship under Ekman's wind-current theory. Easterly winds, which can be expected to retard the North Atlantic Current, would also tend to force warm water northward and westerly winds would drive the surface-water southward.

A relatively simple test of this reasoning will be carried out during the next few years. The changes in dynamic height in the Bermuda region will be followed at selected stations that will be occupied periodically and it should be possible thereby to learn whether or not a decrease in thickness of the central mass of warm water is indeed accompanied by rising sea-surface temperatures in the northeastern area and a strengthening of such movements as the Norwegian Atlantic Current.

If the mechanism outlined above is at all valid, the volume of warm water that must be discharged to the north of the main North Atlantic Eddy during periods of decreasing circulation is surprisingly great as a simple calculation will show. Supposing that the main thermocline at the center of the eddy must rise by 50 meters, which in theory should accompany a general decrease in volume of the surrounding circulation of approximately only 15 per cent, then assuming a mean diameter for the eddy of 2400 km, it turns out that the northern branches of the Gulf Stream System might be strengthened by approximately 226,000 cubic km during the period of the decline. On the other hand, an increase in strength of the North Atlantic Eddy by a similar small percentage might cause a temporary interruption of the movements towards the north with significant consequences to surface-temperatures in the northeastern area.

The chief justification for such speculation is that if the apparently quite steady thermal transfer of the ocean-currents can occasionally cause important climatic and biological variations and if these changes are to be predicted, we must find some mechanisms whereby relatively small variations in the strength of the anticyclonic wind-system over the North Atlantic can produce a relatively great fluctuation in the transport of warm water to the northeastern area.

References

C. O'D. Iselin, 1936, A study of the circulation of the Western North Atlantic, Papers Phys. Ocean. Met., v. 4, No. 4, pp. 1-101.

C. O'D. Iselin, 1937. The new plans for the cooperative investigation of the North Atlantic's circulation, Trans. Amer. Geophys. Union, Eighteenth Annual Meeting, pp. 222-223.

R. B. Montgomery, 1938, Fluctuations in monthly sea-level on the eastern United States coast as related to dynamics of the western North Atlantic Ocean, J. Mar. Res., v. 1, No. 2, pp. 165-185.

Woods Hole Oceanographic Institution,
Woods Hole, Massachusetts

Contribution No. 181

(*Reprinted from* NATURE, *Vol.* 142, *page* 164, *July* 23, 1938.)

Use of Non-Conservative Properties of Sea Water to Physical Oceanographical Problems*

IN applying the eddy diffusion equation to the non-conservative properties of sea water (as distinguished from the conservative properties, the concentrations of which change only as a result of physical processes) a knowledge of the time rates of change in their concentrations (as a result of the biological activity in the water mass) is required. Thus, the form of the equation expressing the effect of vertical turbulence alone on a non-conservative property, such as oxygen, would be :

$$\frac{d\alpha}{dt} = A\frac{\partial^2\alpha}{\partial t^2} - C,$$

where, for dissolved oxygen, α, the term C would represent the rate of oxygen consumption due to the biological activity in the water mass. The consumption of oxygen in the sea as a means of disguising the oxygen transport by turbulence is frequently strikingly brought out at the depths of the oxygen minimum concentration where, regardless of enrichment by eddy diffusion, oxygen concentration actually decreases in the downstream direction due to the greater rate of oxygen consumption.

Information on the rate of oxygen consumption in the depths of the ocean basins is confined chiefly to results obtained for the mid-Atlantic between latitudes 0° and 30° N., where the mean annual oxygen consumption at mid-depths was placed at approximately 0·42 c.c. per litre and that in the deeper water at approximately 0·10 c.c. per litre. Use has been made of the former value in calculating the magnitude of the vertical eddy coefficient at mid-depths (at depth of the minimum oxygen concentration) in the Caribbean basin ; where, with certain assumptions, the gain and loss of oxygen in the downstream direction could be formulated, thus :

$$Ct = O_1 - O_2 + A\frac{\partial^2 O}{\partial t^2}t$$

where Ct represents the amount of oxygen consumed in the downstream direction by biological activity as the water layer (at the depth of the minimum oxygen concentration) moved, during the time, t, from position 1 to position 2 ; $A\frac{\partial^2 O}{\partial t^2}t$, the amount of dissolved oxygen gained as a result of vertical turbulence during the same time (effects due to lateral turbulence are neglected); and $O_1 - O_2$, the observed difference in oxygen concentration (at the depth of the minimum oxygen concentration) between positions 1 and 2. The combination of this equation with a similar one involving the conservative property (salinity) at adjacent depths gave two equations which were solved simultaneously for the values of A and t.

---

* Contribution No. 181 from the Woods Hole Oceanographic Institution.

Substances dissolved in sea water the concentrations of which are altered by biological activity are useful in investigations of its circulation when used either as simple identifying properties or in combination with a conservative property; in such cases it is frequently not necessary to know the rate of the biochemical change of concentration. Particularly useful combinations of conservative and non-conservative properties, such as oxygen and salinity, or oxygen and temperature, may under certain defined conditions be used to trace movements and mixing of water masses and to supplement the results of circulation as calculated from the Bjerknes circulation theorem. The oxygen salinity or oxygen temperature relationship has its counterpart in the temperature salinity relationship (originated by Helland-Hansen), but differs in that the latter strictly conservative relationship is chiefly useful in interpreting combinations of water masses of distinctly different physical properties, whereas the combination of conservative and non-conservative properties may be used advantageously in investigating characteristics of a water mass of marked homogeneity. The latter relationship recently used in an investigation of the water (between approximate depths of 200 and 1,200 metres) in the Caribbean Sea region made it possible to trace the movements and mixing of water masses entering the passages from the open Atlantic and to bring out certain details not clearly indicated by the temperature-salinity relationship.

H. R. SEIWELL.
Woods Hole Oceanographic Institution,
Woods Hole, Massachusetts.
June 14.

Printed in Great Britain by FISHER, KNIGHT & CO., LTD., St. Albans.

Contribution No. 182

THE RELATION OF DISSOLVED OXYGEN TO NITROGEN IN SOME ATLANTIC WATERS

By

NORRIS W. RAKESTRAW AND VICTOR M. EMMEL

*Woods Hole Oceanographic Instituiion**

The use of the oxygen content of sea water to indicate the state of biological activity has become such common practice that one is apt to lose sight of the fact that it is subject to certain qualifications. Since it is based on the assumption that the water was originally saturated with oxygen, the momentary temperature and salinity must be observed, and results are often expressed in terms of "percentage saturation," the ratio of the present content of oxygen to that of water of the same temperature and salinity saturated with oxygen from the atmosphere. In this way, values for "percentage saturation" of more than 100% are frequently obtained. The conditions of this supersaturation must be kept in mind, however; the water is frequently under a very considerable pressure, preventing the actual escape of gas, except at the surface.

Assuming the water to have been saturated by contact with the atmosphere, any subsequent change in its temperature or salinity will produce an apparent change in its "percentage saturation." This may be the result of either the warming of the water from above or mixing with water of different temperature and salinity. A study of the solubility data for oxygen, or any of the other atmospheric gases, shows that the mixing of two water-masses at different temperatures, each saturated with gas, results in water with a gas content greater than the saturation content at the intermediate temperature.

On the other hand, the oxygen may actually increase, as the result of photosynthesis. It is also possible to bring about a state of supersaturation, although only to a slight extent, if the surface water is churned up with very small bubbles of air.

These various effects, however, are small compared with the observed differences in oxygen content of the water, so that the usual uncritical use of oxygen data is adequate for most purposes. But in the case of small oxygen differences it is necessary to have some means of evaluating the effects of the various physical factors if the real change in oxygen content is to be calculated exactly.

It is evident that this can be done by observing one of the more inert atmospheric gases, which is subject to the same physical and hydrographic

---

* Contribution No. 182.

Reprint from SEARS FOUND. JOURN. MAR. RES.

influences as the oxygen, but which is really unchanged by either chemical or biological processes. Nitrogen would seem to be well adapted to this use, since its analytical determination, although more difficult than that of oxygen, is very much easier than that of any of the minor inert gases. Buch (*1*) has done this with some of the oxygen and nitrogen data in the earlier literature and has been able by this means to clear up the relation between assimilation and production of oxygen in some of the more obscure cases.

The increased attention which is now being given to the question of the oxygen minimum layer at deep sea stations, makes it more than ever necessary to be able to distinguish clearly between physical, hydrographic, chemical and biological influences upon the oxygen content.

The analytical determination of nitrogen gas in sea water is not easy, especially if one wishes to separate it from the inert gas fraction (argon, etc.) and not be satisfied simply with the "atmospheric nitrogen" left as residue after removing carbon dioxide and oxygen from dry air. Although this latter step may not be altogether necessary for the purposes described above, we have developed a reasonably simple method of doing so (*3*), primarily for use in some other studies, and have applied it to obtain the pure nitrogen content of water from several deep stations, for comparison with simultaneous oxygen determinations. The original development of such a method for obtaining real nitrogen values, rather than those by difference, was prompted by the feeling that there may very possibly be other inert gases than argon (such as hydrogen, hydrocarbons, etc.) present in some cases. That this was not altogether unwarranted will appear presently.

Buch (*1*) compared the oxygen and nitrogen solubility data from Fox' tables (*2*) and established a relation by which the saturation content of oxygen in water could be readily calculated from the temperature, salinity and nitrogen content. Assuming, then, that the nitrogen in the water has been unaffected by any chemical or biological changes since its original saturation, but that its apparent changes in "percentage saturation" are only the result of temperature and salinity variations in the water, it is possible to calculate a corresponding oxygen content which is the proper base-line from which to measure subsequent changes.

As we have pointed out previously (*4*), our own values for the solubility of pure nitrogen in sea water, as determined by our method, differ significantly from those for "atmospheric nitrogen" in Fox' tables. These revised values are reprinted in Table I. When these data are plotted against oxygen solubility at corresponding temperatures and chlorinities (taken from Fox) a linear relation is obtained between oxygen and nitrogen, which is independent of either temperature or chlorinity, over the range covered. This of course means that over this range the solubilities of both oxygen and nitrogen are affected similarly by changes in temperature and chlorinity. As shown in Fig. 78, therefore, when the nitrogen content is known the corresponding saturated oxygen content may be calculated from the relation: $ccO_2 = .577 \times ccN_2 - .22$.

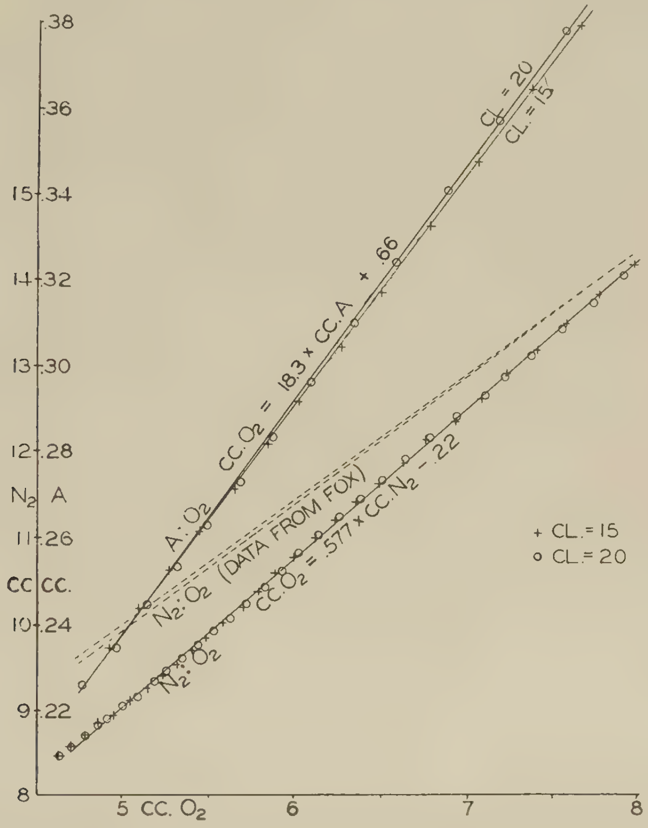


Figure 78. Relation of dissolved oxygen to nitrogen, and to argon, between 0° and 30° C., and chlorinities 15 to 20. Also showing the relation taken from Fox' data for "atmospheric nitrogen" (including argon).

The analytical determination of nitrogen leaves a residue which may also be measured and expressed as argon, although of course it includes any other inert gases as well. From these residual values we have also measured the solubility of crude "argon" in sea water (*4*) and have reprinted the results in Table II. The argon analyses are probably no more accurate than to about 5% under ordinary conditions, which must be kept in mind in the later discussion. However, these data have also been compared with the solubility of oxygen at corresponding temperatures and chlorinities, and Fig. 78 shows a satisfactory linear relation between the two, but varying somewhat with chlorinity. We have accordingly used the "argon" figures also as a basis for the calculation of oxygen, although the results are more erratic and apparently not so well suited to the purpose as are those for nitrogen.

It must be kept in mind that the use of nitrogen values as a basis for the calculation of oxygen is predicated on the assumption that the nitrogen in the water is not affected by either chemical or biological changes. We are now carrying on a study to determine whether or not this is true, and while there are indications that free nitrogen may, under some conditions, undergo small changes, the regularity of the nitrogen content of deep-sea water and its close approximation to a condition of apparent saturation gives no reason as yet to doubt that it is substantially inert in the sea.

An example of this is found at Station 2899, at which the nitrogen content is almost identical with the saturation content at the temperatures throughout the whole water mass. It is evident that concentration equilibrium has been established along the whole column by diffusion of gas, and it would be exceedingly valuable to have a measure of the rate at which this process takes place.

Table III gives the data from several Atlantic stations, including the nitrogen values, obtained by the method mentioned above, as well as the "residual" figures for crude argon (containing other inert gases). Oxygen was determined by the customary Winkler method, for although the volume of dissolved oxygen is also measured in the course of the nitrogen analysis, these volumes will be lower than the true values, since the samples will have stood for some time.

The interpretation of the various symbols heading the columns in the table is as follows:

D = depth in meters

T = temperature in °C.

Cl = chlorinity pro mille

O_2 = observed oxygen content in ccs. per liter

O_2' = saturation oxygen content at the observed T and Cl (from Fox)

$\%O_2$ = "percentage saturation" of oxygen: $100 \times O_2/O_2'$

N_2 = observed nitrogen content

$\%N_2$ = "percentage saturation" of nitrogen: $100 \times N_2/N_2'$

A = observed content of residual crude "argon"

$\%A$ = "percentage saturation" of crude argon (as for N_2 and O_2)

O_2^N = original oxygen content, calculated from the observed N_2, by the relation given in Fig. 78

O_2^A = original oxygen content, calculated from A, by the relation given in Fig. 78

Since physical and hydrographic factors affect the oxygen and nitrogen identically, then, if the nitrogen content has not been altered by chemical or biological changes, it should be possible accurately to calculate the original oxygen content from the nitrogen. The relation of the original oxygen to that observed may be expressed in several ways. A comparison of the "percentage saturation" of the two gases may be made. That of the oxygen will correctly indicate the production or assimilation of oxygen if that of nitrogen does not vary from 100%. It may be seen from the tables that such variation is indeed not great, being significant in a few cases only. The customary uncritical use of the "percentage saturation" of oxygen is therefore justified on the whole, particularly in deep water. In all such cases the difference between O_2 and O_2' is a close measure of the real change in oxygen content. On the other hand, O_2^N, calculated from the nitrogen content, is a more rigorous indication of the original oxygen. The difference between this and the observed oxygen is the corrected, true change in oxygen. Where this difference is positive oxygen has been consumed, where it is negative, as shown here in a few cases, oxygen has been produced in excess of its utilization. And in all such cases, of course, the "percentage saturation" of nitrogen will be greater than that of oxygen.

One of the important outcomes of this method of calculation is the revelation that this predominance of oxygen production over assimilation occurs more rarely than hitherto supposed. This should have some effect upon studies of the relation of photosynthesis to respiration in the sea.

Although similar calculations have been made from the "argon" content it is readily apparent that this function is much less reliable than the nitrogen content. Not only are the figures less accurate but they are erratic for another reason. In the data from Stations 2893 and 2899 the oxygen values calculated from the "argon" are higher than those calculated from the nitrogen in the upper levels, but lower than those calculated from the nitrogen in the deeper samples. It is reasonable to suppose that the "argon" values are somewhat too high in the shallower samples, due to traces of other gases (e.g. hydrogen or hydrocarbons), perhaps the result of the decomposition of plankton, which is present in larger amounts in those samples than the deeper ones.

The figures for the deeper samples at Station 2893 are also somewhat in error, due to another cause. When these samples were analyzed it was noted that small bubbles of air had come out of solution, as the sample-bottles had stood for some time and warmed up. This error, amounting to nearly 5%, affects the nitrogen and "argon" values, but not the oxygen, since the latter had been obtained immediately by the Winkler method. Later, to avoid this, all the deeper, colder samples were stored under pressure, and at low temperature, until analysis, to prevent the escape of gas.

Figures 79, 80 and 81 have been drawn from the data for Stations 2643, 2899 and 2901 to show the relations between the various functions more graphically. It is believed that the curve for $O_2^N - O_2'$ shows the changes in the oxygen content of a water mass most conveniently and accurately.

REFERENCES

1. Buch, K.
1929. Die verwendung von stickstoff- und sauerstoffanalysen in der meeresforschung. Journal du Conseil, vol. 4, no. 2, pp. 162–191.

2. Fox, C. J. J.
1907. On the coefficients of absorption of the atmospheric gases, etc. Publications de Circonstance. Con. Perm. Intern. Exp. Mer. no. 41.

3. Rakestraw, N. W. and Emmel, V. M.
1937. The determination of dissolved nitrogen in sea water. Industrial and Engineering Chem. (Anal. Edit.), vol. 9, p. 344.

4. Rakestraw, N. W. and Emmel, V. M.
1938. The solubility of nitrogen and argon in sea water. Journal of Physical Chemistry. (In press.)

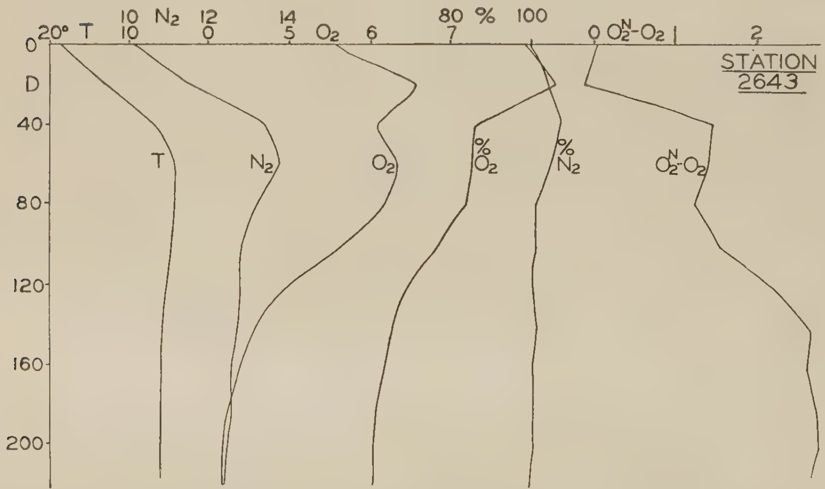


Figure 79. Vertical distributions at Station 2643 of Temperature (T), Nitrogen (N_2), Oxygen (O_2) and the difference between original oxygen contents calculated on the basis of nitrogen present and the observed oxygen contents ($O_2^N - O_2$). Nitrogen and Oxygen expressed in absolute values at the left and in per cent relative saturations at the right. Scales for absolute N_2, O_2 and $O_2^N - O_2$ in cc. per liter. Depths in meters.

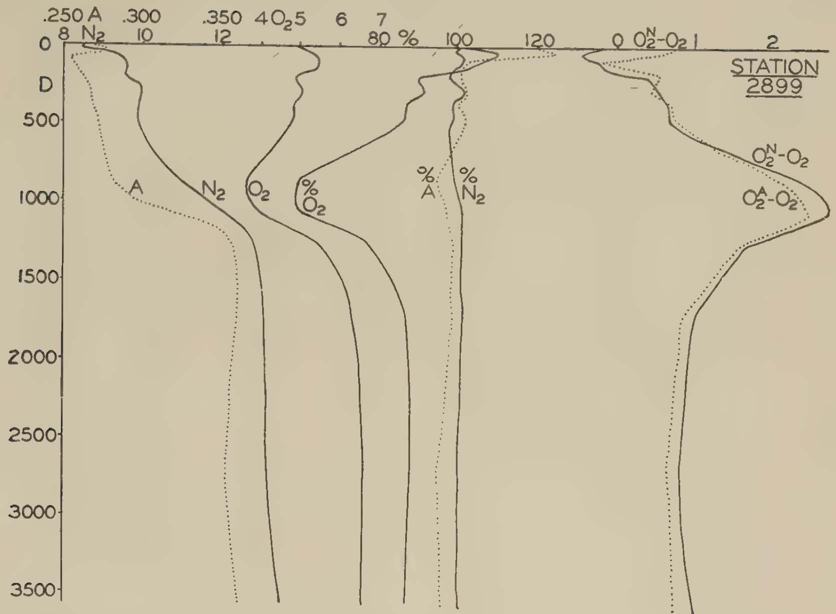


Figure 80. Vertical distributions at Station 2899. (A) Argon. $(O_2^A - O_2)$ difference between original oxygen contents calculated on the basis of Argon present and the observed oxygen contents. For further explanations see legend of Figure 79.

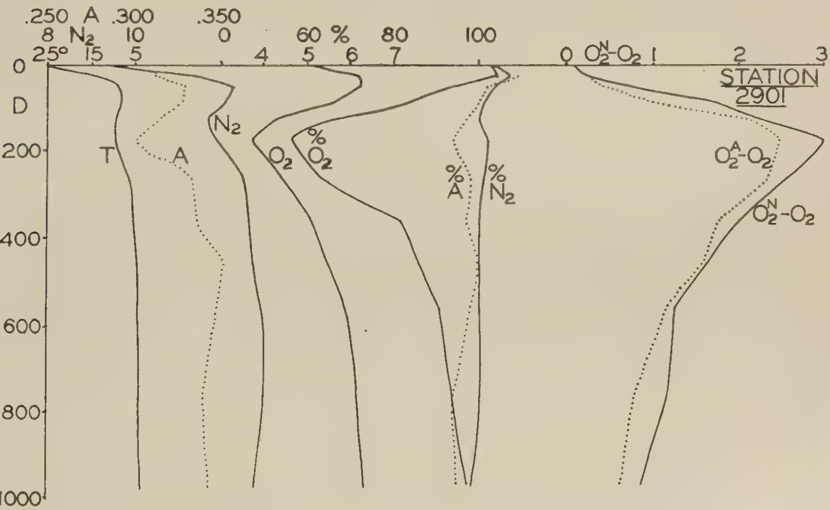


Figure 81. Vertical distributions at Station 2901. See legends of Figures 79 and 80.

TABLE I

Solubility of Nitrogen in Sea Water

(Cc. at S.T.P. per 1000 cc. of Water, from a Normal Atmosphere of 760 mm.)

T *Cl*	*15*	*16*	*17*	*18*	*19*	*20*	*21*
0°	15.22	15.02	14.82	14.61	14.40	14.21	14.01
1	14.81	14.61	14.42	14.23	14.04	13.85	13.66
2	14.43	14.24	14.06	13.88	13.69	13.51	13.33
3	14.07	13.89	13.72	13.54	13.36	13.19	13.01
4	13.73	13.56	13.40	13.24	13.06	12.89	12.72
5	13.43	13.26	13.10	12.94	12.78	12.62	12.45
6	13.14	12.98	12.82	12.67	12.51	12.35	12.19
7	12.88	12.72	12.56	12.41	12.26	12.10	11.95
8	12.62	12.47	12.32	12.17	12.02	11.87	11.71
9	12.38	12.23	12.08	11.94	11.79	11.64	11.49
10	12.15	12.00	11.86	11.71	11.56	11.42	11.27
11	11.92	11.78	11.63	11.49	11.34	11.20	11.06
12	11.69	11.56	11.42	11.28	11.13	10.99	10.85
13	11.47	11.34	11.21	11.07	10.93	10.79	10.65
14	11.25	11.13	10.99	10.86	10.73	10.59	10.45
15	11.04	10.92	10.79	10.66	10.53	10.39	10.26
16	10.83	10.72	10.59	10.47	10.34	10.21	10.08
17	10.63	10.52	10.40	10.28	10.15	10.03	9.91
18	10.44	10.33	10.21	10.10	9.98	9.86	9.74
19	10.26	10.15	10.03	9.92	9.81	9.69	9.58
20	10.08	9.98	9.87	9.76	9.65	9.54	9.43
21	9.91	9.82	9.71	9.61	9.50	9.39	9.28
22	9.75	9.66	9.56	9.46	9.35	9.24	9.14
23	9.60	9.51	9.41	9.31	9.20	9.10	9.00
24	9.45	9.36	9.26	9.16	9.06	8.96	8.86
25	9.30	9.21	9.11	9.02	8.92	8.82	8.73
26	9.16	9.07	8.97	8.88	8.79	8.69	8.60
27	9.02	8.94	8.84	8.75	8.66	8.56	8.47
28	8.89	8.84	8.72	8.62	8.53	8.44	8.35

TABLE II

Solubility of Argon in Sea Water

(Cc. at S.T.P. per 1000 cc. of Water from a Normal Atmosphere of 760 mm.)

T *Cl*	*15*	*16*	*17*	*18*	*19*	*20*	*21*
2°	.405	.400	.395	.389	.384	.379	.373
4	.384	.379	.374	.369	.363	.358	.352
6	.365	.360	.355	.350	.345	.340	.335
8	.347	.343	.338	.333	.329	.324	.319
10	.331	.327	.323	.318	.314	.310	.305
12	.317	.313	.309	.304	.300	.296	.292
14	.304	.300	.296	.292	.288	.284	.280
16	.292	.288	.284	.280	.277	.273	.269
18	.282	.278	.274	.270	.267	.263	.259
20	.272	.268	.264	.260	.256	.253	.249
22	.262	.258	.255	.251	.247	.244	.240
24	.253	.249	.246	.242	.238	.235	.231
26	.244	.240	.237	.233	.229	.226	.222
28	.235	.231	.228	.224	.220	.217	.213

TABLE III

D	T	Cl	O_2	O_2'	$\%O_2$	N_2	N_2	A	%A	O_2^N	O_2^A	$O_2^N-O_2$	$O_2^A-O_2$
Station 2643					42°—19′ N; 19°—20′ W					August 10, 1936			
0	18.3	17.6	5.58	5.63	99	10.13	100			5.61		.03	
20	13.0	17.8	6.56	6.17	106	11.50	104			6.42		−.14	
40	6.5	18.1	6.06	7.01	86	13.45	107			7.54		1.48	
60	4.2	18.2	6.32	7.38	85	13.8	105			7.74		1.42	
80	4.2	18.2	6.18	7.38	84	13.22	101			7.42		1.24	
100	4.5	18.4	5.66	7.31	77	12.85	101			7.20		1.54	
120	5.2	18.55	4.97	7.17	69	12.80	100			7.17		2.20	
140	5.7	18.7	4.60	7.08	65	12.76	101			7.26		2.66	
160	5.9	18.75	4.40	7.04	63	12.60	100			7.05		2.65	
180	6.1	18.9	4.24	7.00	61	12.58	100			7.03		2.79	
200	6.1	18.9	4.19	7.00	60	12.50	100			7.00		2.81	
220	6.1	18.9	4.21	7.00	60	12.42	99			6.95		2.74	
Station 2666					39°—00′ N; 70°—00′ W					September 3, 1936			
0	20.90	18.3	5.19	4.98	104	9.72	108			5.38		.19	
10	22.50	18.7	5.04	5.19	97	9.50	102			5.26		.22	
20	11.93	18.6	6.11	6.23	98	11.7	105			6.59		.48	
39	13.34	19.15	4.35	5.92	74	11.0	103			5.93		1.58	
59	12.46	18.85	4.29	6.13	70	11.0	100			6.16		1.87	
78	12.05	19.3				10.8	97						
87	12.31	19.0	4.04	6.16	66	11.1	100			6.18		2.14	
135	7.85	19.1	3.90	6.71	58	11.4	95			6.36		2.46	
183	9.57	19.3	3.20	6.48	49	11.7	101			6.53		3.33	
279	7.71	19.0	4.04	6.75	60	12.4	103			6.93		2.89	
375	5.23	18.9	4.84	7.13	68	12.6	99			7.05		2.21	
471	4.68	19.0	5.19	7.21	72	12.7	99			7.11		1.92	
552	4.69	18.95	5.31	7.21	74	12.5	97			6.99		1.68	
736	4.23	18.9	5.73	7.13	80	12.6	99			7.05		1.32	
921	4.02	19.2	6.02	7.31	82	12.5	96			6.99		0.97	
1105	4.12	19.3	6.08	7.31	83	12.8	98			7.17		1.09	
1381	3.58	19.0	5.90	7.40	80	12.8	97			7.17		1.27	
1845	3.34	18.8	6.21	7.44	84	13.0	98			7.28		1.07	
2762	2.56	19.05	6.24	7.58	82	13.3	98			7.45		1.21	
Station 2667					35°—31′ N; 69°—15′ W					September 5, 1936			
10	26.05	19.8	4.61	4.80	96	8.83	101			4.82		.21	
60	20.91	20.0	5.27	5.22	101	9.67	103			5.36		.09	
180	18.20	19.7	4.72	5.47	86	9.64	98			5.34		.62	
449	17.29	19.5	4.47	5.60	80	10.3	102			5.73		1.26	
719	14.77	19.4	4.10	5.83	70	10.4	101			5.88		1.78	
899	11.54	19.05	3.36	6.20	54	11.3	101			6.30		2.94	
1348	5.18	19.0	5.12	7.13	72	12.6	101			7.05		1.93	
3595	3.14	19.2	6.08	7.47	81	13.9	104			7.88		1.80	

TABLE III (Continued)

Station 2893 35°—30′ N; 67°—17′ W July 12, 1937

D	T	Cl	O_2	O_2'	$\%O_2$	N_2	N_2	A	$\%A$	O_2^N	O_2^A	$O_2^N-O_2$	$O_2^A-O_2$
0	26.5	20.07	4.65	4.73	98	8.8	102	.250	111	4.86	5.23	.21	.58
50	24.0	20.25	5.20	4.93	106	9.3	104	.260	110	5.14	5.41	−.06	.21
100	19.0	20.2	4.97	5.39	92	9.7	100	.270	109	5.38	5.59	.41	.62
150	18.5	20.2	4.86	5.43	90	9.9	101	.280	108	5.49	5.77	.63	.91
200	18.2	20.2	4.80	5.46	88	10.05	102	.290	111	5.58	5.96	.75	1.16
300	17.8	20.2	4.70	5.50	86	10.15	102	.320	120	5.64	6.50	.94	1.80
400	17.5	20.15	4.65	5.53	84	9.9	101	.290	108	5.53	5.95	.88	1.30
500	16.7	20.1	4.40	5.56	79	10.2	101	.295	109	5.66	6.06	1.26	1.66
600	15.5	19.95	4.10	5.74	72	10.4	101	.290	105	5.78	5.96	1.68	1.86
800	11.5	19.57	3.50	6.22	56	11.3	101	.315	104	6.29	6.41	2.79	2.91
1000	7.5	19.42	4.10	6.74	61	12.3	101	.335	101	6.87	6.78	2.77	2.66
1500	4.2	19.37	5.84	7.26	81	12.6	98	.340	96	7.01	6.68	1.17	1.02
2000	3.5	19.35	6.20	7.37	84	12.7	97	.345	94	7.10	6.95	.90	.75
2500	3.3	19.35	6.20	7.41	84	12.75	97	.350	95	7.13	7.04	.93	.84
3000	3.0	19.32	6.10	7.47	82	12.8	96	.350	94	7.16	7.04	1.06	.94
3500	2.8	19.32	6.07	7.51	81	12.9	96	.355	95	7.22	7.13	1.15	1.06
4000	2.5	19.32	6.00	7.56	79	12.95	96	.355	94	7.26	7.13	1.26	1.13
4500	2.3	19.30	5.90	7.60	78	13.0	96	.360	95	7.28	7.22	1.38	1.32

Station 2899 36°—01′ N; 69°—57′ W August 8, 1937

D	T	Cl	O_2	O_2'	$\%O_2$	N_2	N_2	A	$\%A$	O_2^N	O_2^A	$O_2^N-O_2$	$O_2^A-O_2$
1	27.37	19.99	4.79	4.67	102	8.60	101	.266	121	4.75	5.52	−.04	.73
23	27.06	20.05	5.05	4.70	107	8.52	100	.275	124	4.70	5.69	−.35	.64
46	25.54	20.14	5.28	4.82	110	8.75	101	.274	120	4.83	5.67	−.45	.39
93	20.97	20.21	5.51	5.20	106	9.51	102	.254	103	5.28	5.30	−.23	−.21
139	19.64	20.24	5.45	5.34	102	9.60	100		101	5.32		−.13	
185	18.84	20.20	4.88	5.40	90	9.52	98	.261	101	5.28	5.42	.40	.54
278	18.25	20.20	5.03	5.46	92	9.96	102	.266	102	5.53	5.46	.50	.43
371	17.89	19.43	4.83	5.54	87	9.89	99	.267	100	5.49	5.52	.66	.69
464		20.17	4.81	5.53	87	9.84	99	.271	102	5.46	5.54	.65	.73
556	16.87	20.11	4.61	5.60	82	9.92	98	.272	101	5.51	5.61	.90	1.00
861	12.36	19.70	3.63	6.09	60	10.80	99	.279	94	6.02	5.76	2.39	2.13
1076	7.78	20.19	3.89	6.62	59	11.95	101	.315	97	6.68	6.41	2.79	2.52
1291	4.98	19.37	5.52	7.12	77	12.82	101	.356	99	7.19	7.11	1.67	1.59
1722	3.96	19.36	6.31	7.29	87	13.05	101	.358	99	7.32	7.16	1.01	.85
2690	3.31	19.36	6.57	7.40	88	13.13	100	.353	95	7.36	7.20	.79	.63
3773	2.55	19.36	6.52	7.57	86	13.49	100	.362	96	7.57	7.27	1.05	.75

Station 2901 39°—40′ N; 71°—43′ W August 11, 1937

D	T	Cl	O_2	O_2'	$\%O_2$	N_2	N_2	A	$\%A$	O_2^N	O_2^A	$O_2^N-O_2$	$O_2^A-O_2$
1	25.05	17.78	5.14	5.01	103	9.43	104			5.23		.09	
25	14.62	18.46	6.18	5.93	104	11.42	107	.314	109	6.38	6.40	.20	.22
50	8.50	19.47	6.25	6.60	95	12.32	104	.329	102	6.89	6.68	.64	.43
87	8.42	18.79	5.59	6.66	84	12.10	101	.326	100	6.76	6.62	1.17	1.03
131	9.49	19.24	4.27	6.48	66	11.70	100	.314	100	6.53	6.40	2.26	2.13
176	9.22	19.38	3.64	6.51	56	11.91	102	.299	94	6.66	6.13	3.02	2.49
268	6.40	19.33	4.40	6.92	63	12.48	101	.332	98	6.98	6.73	2.58	2.33
363	5.40	19.33	5.06	7.07	72	12.62	100	.336	97	7.06	6.80	2.00	1.74
460	4.87	19.34	5.50	7.15	77	12.73	100	.352	100	7.13	7.10	1.63	1.60
560	4.48	19.39	5.87	7.21	81	12.89	100	.348	98	7.21	7.02	1.24	1.15
768	4.22	19.35	6.12	7.26	84	12.96	100	.340	94	7.26	6.87	1.14	.75
977	3.98	19.36	6.32	7.29	87	12.73	98	.343	95	7.13	6.93	.81	.61

Contribution No. 183

Reprinted from Biological Bulletin, Vol. LXXV, No. 1, 106–118, August, 1938
Printed in U. S. A.

THE EFFECT OF LIGHT ON THE VERTICAL MOVEMENTS OF ACARTIA CLAUSI (GIESBRECHT)

W. H. JOHNSON

(From the Atlantic Biological Station at St. Andrews and the Woods Hole Oceanographic Institution, Woods Hole, Mass.)

THE EFFECT OF LIGHT ON THE VERTICAL MOVEMENTS OF ACARTIA CLAUSI (GIESBRECHT)[1]

W. H. JOHNSON

(From the Atlantic Biological Station at St. Andrews and the Woods Hole Oceanographic Institution, Woods Hole, Mass.)

The changing vertical distribution of plankton Crustacea has long received a great deal of attention; copepods in particular have been the object of much study. Although many factors have been proposed to account for vertical migrations, it is now generally recognized that light is the chief instigator. The complexity of the affair, however, has been frequently discussed by such outstanding authors on the subject as F. S. Russell of Plymouth and G. L. Clarke of Woods Hole. The apparent lack of persistent responses makes it highly desirable to collect more facts dealing with the rôle played by light and it was with this end in view that the following studies were made on the marine copepod, *Acartia clausi.*

FIELD STUDIES

Field studies were carried out during the summers of 1935 and 1936, the collections of the first summer being confined to the head (Big Bay) while those of the second summer centered close to the mouth (off Bain's Island) of Inner Passamaquoddy Bay.

Methods

The two stations were established in regions devoid of any strong tidal currents which might complicate the results. The vertical distributions were determined under various conditions of light by collecting samples at four different depths for each condition of light.

The nets were made from No. 5 bolting cloth. By a special contrivance, it was possible to collect the organisms only at the specific depths; no such device was necessary for the surface tow. The arrangement for opening and closing the nets is shown in Fig. 1. The net is lowered to the specific depth by means of the line "a" which is kept taut, while line "b" runs out freely. In this way the net descends vertically due to the weight "w." On reaching the desired depth, a messenger is let down line "b" thereby releasing the attached mechanism. The net thus takes up the second position and line

---

[1] Contribution No. 183 from the Woods Hole Oceanographic Institution.

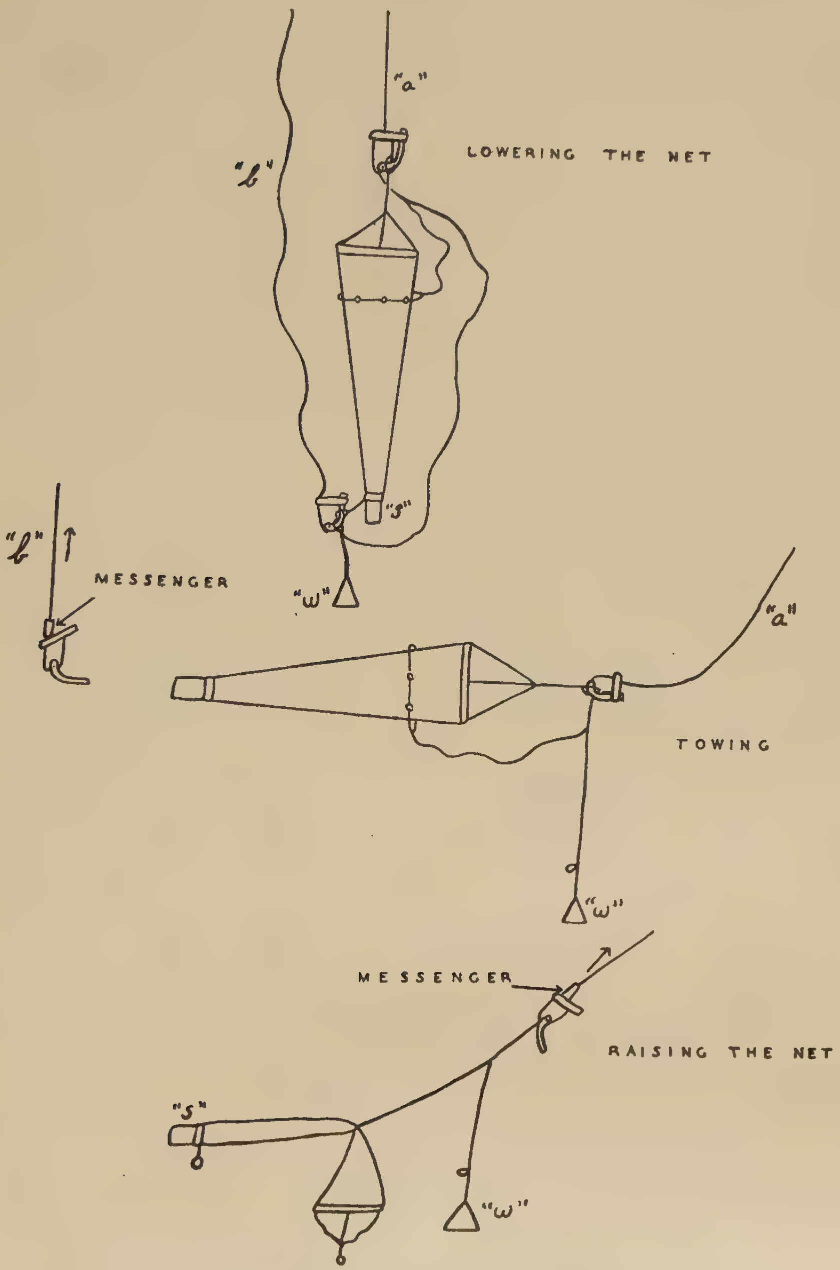

"a"
"b"
LOWERING THE NET
"s"
"w"
"b"
MESSENGER
"a"
TOWING
"w"
MESSENGER
RAISING THE NET
"s"
"w"

FIG. 1. *Closing mechanism used with the nets.*

"b" is withdrawn into the boat. The boat now slowly moves forward causing the net to strain the water. As nearly as can be judged, a definite and constant velocity of the boat is maintained. At the end of ten minutes a messenger is let down line "a" causing the net to be closed and the whole arrangement is withdrawn into the boat. The contents of the net are then carefully washed into the pint sealer "s," preserved in 4 per cent formaldehyde, and labelled.

Just before the nets were towed, the light intensity incident at the surface was measured by means of a solarimeter. This instrument is made by Kipp and Zonen, Delft, Holland. The light-receiving unit is a Moll surface thermopile covered with a hemispherical quartz window. The current produced is measured by means of a micro-ammeter. On a clear day this instrument will measure the intensity of sunlight from sunrise to sunset. The units of light intensity recorded are percentages of full noon June sunlight (F.N.J.S.), i.e. in percentage of the highest reading of noon June sunlight.

The transparency of the water was measured by means of a Secchi disk. It always disappeared from view at 16 feet.

The contents of the pint sealers were treated in the laboratory as follows: permitted to settle in a graduate to determine total volume; thoroughly shaken so as to produce a homogeneous mixture, and exactly 5 cc. removed by means of a Stempel pipette; the 5 cc. sample placed on a specially constructed counting cell, and the copepods identified and counted. At least two counts were made, except when there was so little plankton present that the whole tow was counted without making use of the Stempel pipette. The results of the counts were averaged. If the counts were within 10 per cent of their average, no further counts were made. The counts, when specimens were numerous, always showed close agreement. It was, however, often found necessary to make as many as six counts of the scarcer forms.

Each copepod was determined as being male, female, or young. For the purpose of identification, the following authors were consulted: (*a*) Sars—"Crustacea of Norway," and (*b*) Wilson—"Copepods of the Woods Hole Region." Such identification was not difficult as no very young forms were present in the tows, and the young found were sufficiently like the adults not to be easily confused as to species. The size, shape of fifth leg, antennule, and number of segments of the urosome were the characters mostly used for identification. The counting cell was so shallow that the copepods usually lay on their sides, thus exposing the fifth leg. A drop of dilute aqueous solution of methylene blue, added to the contents of the counting cell, greatly facilitated counting of the segments and recognition of the shape of the fifth legs.

Results

Consecutive Samples:—The results of a 24-hour series taken off Bain's Island on September 2 and 3, 1936, are shown in Fig. 2.

During the morning of September 2, the sunlight intensity was increasing rapidly so as to reach 60 per cent F.N.J.S. by 10 A.M. Males, females, and young were all absent from the surface with the young, on the whole, not as far down as the adults.

By 2 P.M. the intensity had increased to a maximum of 78 per cent F.N.J.S. Occasional clouds in the sky, however, cut the intensity down to about 28 per cent F.N.J.S. when crossing before the sun. However, the prodominant light intensity was the maximum value recorded, and it is seen that males, females, and young are now in proportionately greater numbers at the bottom than before.

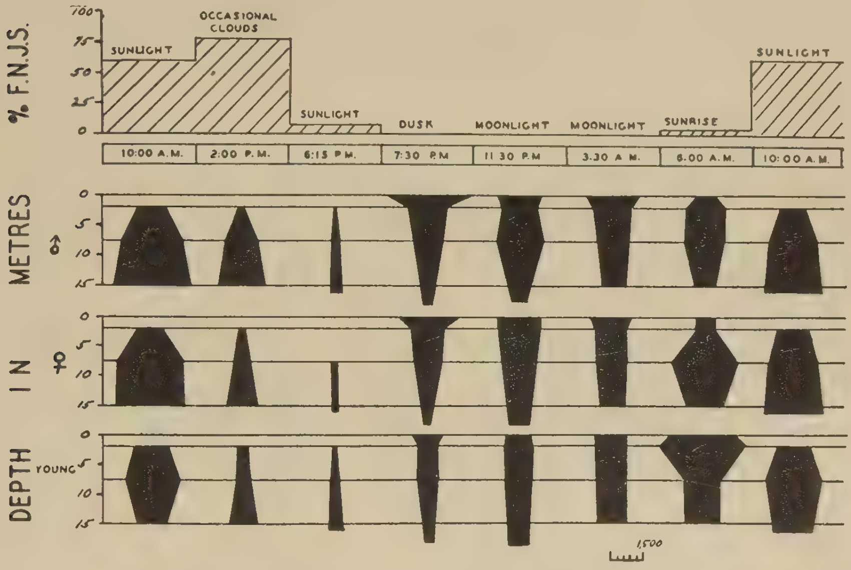


FIG. 2. The vertical distributions of males, females, and young over a period of twenty-four consecutive hours in September of 1936.

During the late afternoon, the sunlight was decreasing rapidly so that at 6:15 P.M. the light was 7 per cent F.N.J.S. Unfortunately, low numbers were captured by the nets at the time and some justification is felt for believing that the true picture of vertical distribution is not presented here.

A considerable drop in intensity occurred in the late evening so that by 7:30 P.M. a condition considered as dusk prevailed. The photometer would not register at this low intensity; the visibility was very poor. During these conditions it is quite evident that a decided upward migration for males, females, and young had taken place so that decided maxima now occurred directly at the surface.

Shortly after 7:30 P.M. the full moon had appeared over the hills and by 11:30 P.M. visibility was good. Thus there was an increase in light intensity from 7:30 to 11:30 P.M. and on comparing the distributions at these two times males, females, and young alike appear to show a downward migration from the surface. It may be, however, that the moonlight had no effect and the animals were becoming uniformly distributed.

Moonlight prevailed throughout the rest of the night till 5:00 A.M. and tows taken at 3:30 A.M. indicate a decided tendency for uniform distribution of males, females and young. Thus continued moonlight does not result in their concentrating at any one particular depth.

At 6 A.M. the sun had risen over the hills causing an increase in light intensity as compared to the condition during the previous night. Males, females, and young all showed a downward migration from the surface with the young least affected, then the males, and finally the females. That is, the young showed a maximum at 2 meters, the males from 2 to 7½ meters, and the females at 7½ meters.

The sunlight continued to increase in intensity until by 10 A.M. it had reached 60 per cent F.N.J.S. Males, females, and young had descended still deeper into the water as compared with the condition at 6 A.M., with the males and females now showing maxima at the bottom and the young at 7½ meters. The young were still less affected by this condition than the adults. The vertical distributions are similar to those which obtained the previous day at 10 A.M. when the same light conditions prevailed.

Another series of consecutive tows was taken during the summer of 1935, the results of which are given in Fig. 3. During the late afternoon, the sunlight intensity was decreasing from 75 per cent at 2:40 P.M. to 27 per cent F.N.J.S. at 5:40 P.M. The two-meter tow taken at 2:40 P.M. was unfortunately destroyed. Nevertheless, it is evident that a decided upward migration had taken place for males, females, and young directly to the surface at 5:40 P.M.

The moon, which was two-thirds full, had been up all evening and so the light intensity was decreasing more slowly than had there been no moon. On comparing the vertical distributions of 8:55 P.M. with those which obtained at 5:40 P.M., it seems that a downward migration was taking place from the surface—possibly the result of the rate of decrease being so low as to no longer attract the animals up to the surface such as occurred somewhat earlier in the evening, i.e. the rate of decrease must have been below their threshold (Clarke, 1930). It might have been, had the light continued as it was at 8:55 P.M., that the animals would later have become uniformily distributed. However, the moon set shortly before midnight so that the condition at 12:10 A.M. represents a decrease in light intensity. Here we have evidence of an upward migration in the upper layers to the surface—a migration particularly evident for the males and young.

During continued starlight conditions, males, females, and young tended to sink slowly in the water as seen by the condition at 3:20 A.M.

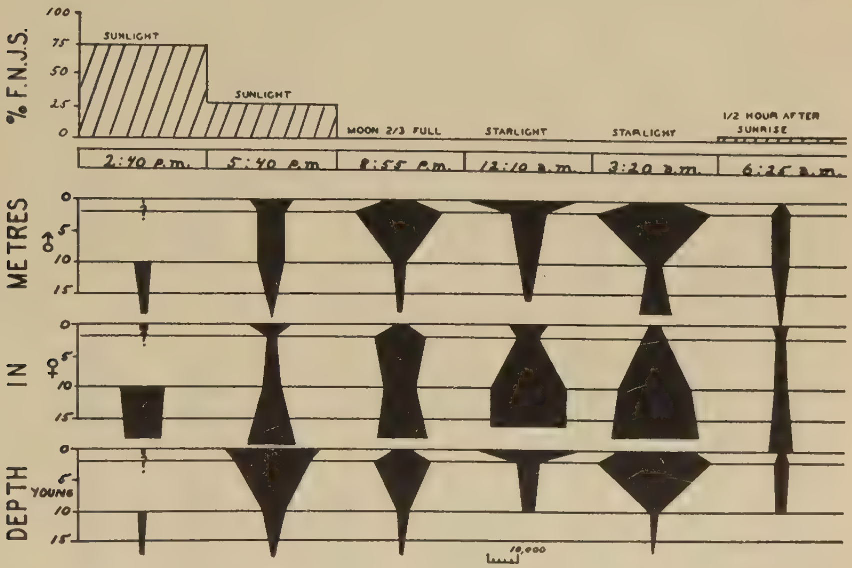


FIG. 3. The vertical distributions of males, females, and young during consecutive hours in August of 1935.

With the sunlight increasing in intensity in the early morning, reaching 3 per cent F.N.J.S. at 6:25 A.M., and comparing the vertical distributions with those at 3:20 A.M., it is quite evident that a great decrease in numbers had taken place in the upper levels. Although the animals appear to be more or less uniformly distributed, it is believed that a downward migration is in the process of being carried out, a fact which would have been made more evident had the tows been taken somewhat later (cf. Fig. 2 at 10 A.M.).

Occasional Samples:—From the above results it is seen that upward migration occurs under decreasing light, while downward migration occurs under increasing light. Although similar vertical distributions were found to occur on different days when the light intensities were the same, it soon became evident that this is not always the case. Thus at sunrise on August 1 (Fig. 4), the animals were all farther down than at sunrise on September 3 (Fig. 2) even though the light intensity was the same on each occasion. However, the light intensities preceding sunrise were different on the two occasions; in the former case there had been no moonlight from 2:30 A.M. on, while in the latter case there had been full moonlight all night until one-half hour before sunrise. In other words, following the greater increase in light intensity the animals descended farther down.

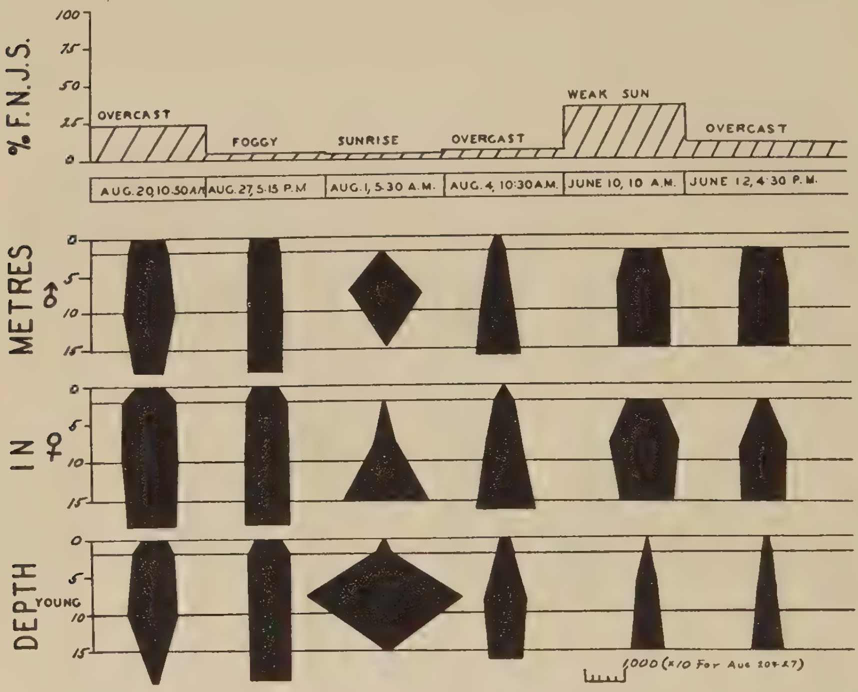


Fig. 4. The vertical distributions of males, females, and young as determined by occasional tows.

More examples indicating the difficulty of explaining vertical distributions on a basis of optimum intensity were found. For example, on June 12 at 4:30 P.M. males, females, and young showed practically the same vertical distributions as on June 10 at 10 A.M. (Fig. 4) even though the light intensities were decidedly different on the two occasions (10 per cent and 35 per cent F.N.J.S. respectively).

Increasing light apparently drives the animals down from the surface. When the light is steadily increasing in the morning, the higher the light intensity the farther down the animals are found (as has already been shown). However, this relationship between light intensity and depth does not necessarily hold when we compare the vertical distributions at the same time of the morning on two separate days having different intensities. This is well shown in Fig. 4. On August 20 at 10:50 A.M. males, females, and young were all, on the whole, nearer to the surface than at 10:30 A.M. on August 4, even though the light intensity was much higher on the former occasion (25 per cent F.N.J.S. as contrasted with 5 per cent F.N.J.S.).

Laboratory Experiments

Laboratory experiments, the results of which might prove to be of value in attempting to interpret the behavior of *Acartia clausi* in nature, were carried out in the basement of the Atlantic Biological Station during the latter part of September, 1936.

We have seen cases where reliable results showed that similar vertical distributions can take place under different light intensities. This fact was noted for males, females, and young alike of the same species and in the same locality. If the animals change their vertical distributions with changes of light intensity, is the direction of migration such as to bring them into a region of the same light intensity as that in which they existed formerly? Or, in other words, is there an optimum intensity for which the species is continually seeking? The very fact that similar vertical distributions can be found under different light intensities may answer the question in the negative in certain cases. However, to test the question somewhat more extensively, it was decided to study their vertical distributions under controlled conditions of light in the laboratory.

Methods and Results

Two tows were made off the Atlantic Biological Station wharf at St. Andrews at 4 P.M. during bright sunlight of intensity 50 per cent F.N.J.S. at the surface. The tows were made at the surface catching a few hundred *Acartia clausi.* Very few of any other species were present, *Acartia* being dominant in this region. In a quiet region it would be difficult to obtain *Acartia* at the surface under such conditions, but due to swift tidal currents they are forced up to the surface here.

Each tow was placed in a separate glass cylindrical glass jar of about 20 inches in length and 5 inches in internal diameter. Tar paper was placed around and below each jar so that light could only come in from the top. A piece of thin glass was placed just above the open upper end of each jar so as to absorb heat from the electric light bulb when the latter was close to the jar. Over each jar was placed an electric light bulb of 50 watts, capable of being raised or lowered through a distance of 5 feet above the surface of the water in each jar. The arrangement was set up in a constant temperature room. The temperature of the water in the jars was thus kept the same as the water in nature from which the copepods had been removed (12° C.).

Effects of Single Changes in Intensity

Over one jar the electric light bulb was placed at a distance of 5 feet from the surface, while over the other a bulb was fixed a foot from the surface. The animals which had been obtained from the surface under bright sunlight were allowed ten minutes to distribute themselves and then the vertical distributions were determined by counting the numbers seen during a period of one minute through a square hole (1/4 inch square) in the tar paper. Such a count was made for each quarter-length of the jar. The resulting vertical distributions are shown in the following table:

	Bulb at 1 foot	Bulb at 5 feet
Section I (upper)	22	60
Section II	16	2
Section III	16	2
Section IV (lower)	1	2

The animals were subjected, as a result of the above procedure, to a decrease in light intensity in each case (sunlight intensity at the surface in nature was 50 per cent F.N.J.S., while a 50-watt bulb, when placed at a distance of one foot from the photometer, produced a reading of 4 per cent F.N.J.S., the intensity at a distance of 5 feet being 0.18 per cent F.N.J.S.). It is seen from the above that both changes in light intensity resulted in upward movement the extent of which was greater following the larger decrease in intensity. The individuals were uniformly distributed in the jars before being taken into the laboratory.

The electric bulbs were then left in the above positions until 2:30 P.M. the next day, and on examining the vertical distributions it was found that the individuals were uniformly distributed in each jar. The results point to a decrease in light intensity as the stimulus for upward migration and the greater the change in light the greater the upward movement. Furthermore, they indicate that the animals were not seeking an optimum intensity since they became uniformly distributed when left for some time under the intensity in which they first moved upward.

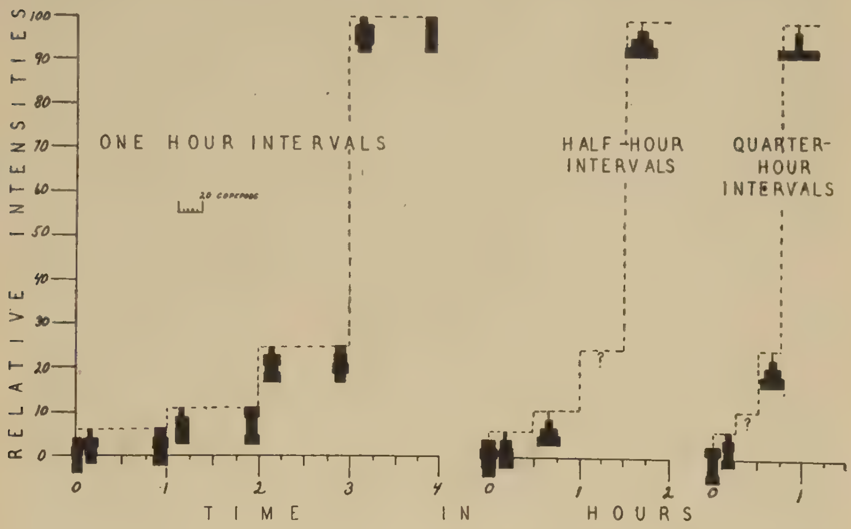


FIG. 5. The vertical distributions in glass jars resulting from increasing the light intensities at different frequencies.

The positions of the bulbs were then reversed so that the bulb previously at the surface was raised to 5 feet causing a decided decrease in light intensity, while the bulb previously at 5 feet was lowered to 1 foot from the surface causing an increase in light intensity. The vertical distributions ten minutes after the changes were made are shown in the following table:

	Bulb at 5 feet	Bulb at 1 foot
Section I (upper)	28	1
Section II	14	4
Section III	5	14
Section IV (lower)	1	30

The results show that a decrease in light intensity resulted in upward movement while an increase in light induced downward movement. The magnitudes of increase and decrease in both cases were the same and it is interesting to note that the resulting vertical distribution of the one is practically the inverse of the other. The bulbs were left this way until 9 A.M. the following morning and on examination a uniform vertical distribution was found in each jar. Thus it again appears that a change in light intensity is necessary to evoke migration of *Acartia*, while under static conditions no movement occurs.

Effects of Repeated Changes in Intensity

Increasing Light:—With the animals uniformly distributed and the bulb at 5 feet, the light intensity was increased by lowering the bulb 1 foot every hour, 1 foot every half-hour, and one foot every 15 minutes. The vertical distributions were determined shortly after each change was made, and in the case of one-hour intervals, readings were also made just before the next change. The results are shown in Fig. 5.

Decreasing Light:—With the animals uniformly distributed and the bulb at 1 foot, the light intensity was decreased by raising the bulb one foot every hour, one foot every half-hour, and one foot every 15 minutes. Readings were taken of the vertical distributions 10 minutes after each change was made, and in the case of one-hour intervals, readings were also made just before the next change. The results are shown in Fig. 6.

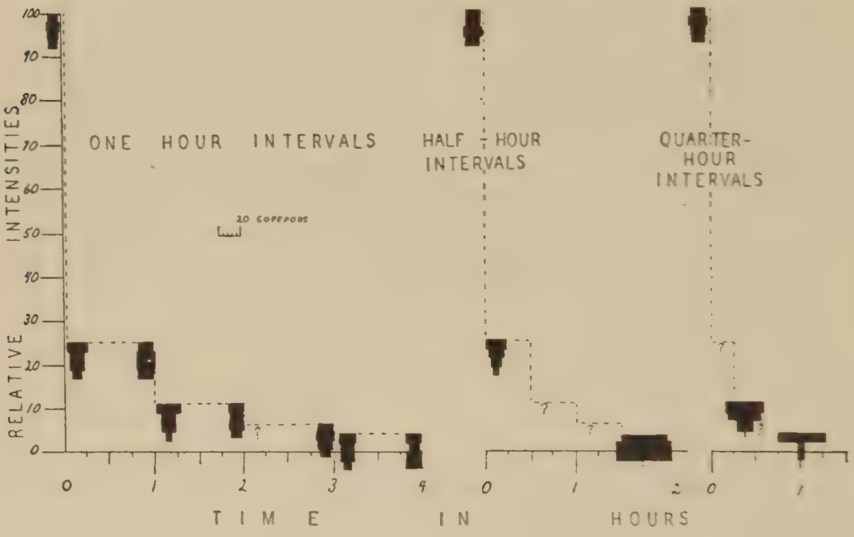


FIG. 6. The vertical distributions in glass jars resulting from decreasing the light intensities at different frequencies.

It is seen from the above two experiments, that on increasing or decreasing the light intensity by lowering or raising the bulb one foot every hour, slight but noticeable changes were produced in the vertical distributions of the copepods soon after each change was made, but that the animals returned to uniform vertical distribution before the next change was made. In the case of the half-hour intervals, the animals did not return to uniform vertical distribution but gradually increased or decreased the distance at which the majority were found from the surface; the same applies to the 15-minute intervals except that the movements were more pronounced.

It is thus seen that when the light intensity remained the same for some time before the next change was made, the animals returned to uniform vertical distribution; but if the next change followed soon enough the animals continued to move either up or down, as the case may be, and the more frequent the changes the more pronounced the effect.

Examples are also seen where similar vertical distributions occurred under different light intensities, and also examples of different vertical distributions under similar light intensities.

Discussion

While the vertical distributions of *Acartia clausi* in nature were found to present some puzzling problems, it appears that some importance might be placed upon the direction and rapidity of change of light intensity, i.e., downward migration may be brought about by increasing light intensity while upward migration may be brought about by decreasing light, and some instances were found which suggest that the more rapid the change of intensity, the greater the response induced.

It is realized that the changes of light intensity produced in the experiment do not represent different rates of change but were merely different frequencies of change, and each change in itself was more sudden than usually occurs in nature (except possibly the sudden increase and decrease of light as the result of a cloud passing across the sun). Furthermore, it is realized that during any one series of changes the different magnitudes of change were in no two cases equal; thus the experiment does not represent the effects of similar magnitudes of change merely being applied at different frequencies. Taking everything into consideration, the results of the experiment are not strictly applicable to light changes as they usually occur in nature. Nevertheless, they do suggest that *Acartia clausi* requires *changes* in intensity to evoke vertical migration and the more frequently the changes occur the more the animals are stimulated to move either toward or away from the light as the case may be.

An interesting fact not already mentioned is that *Acartia* moved toward an electric light (or bright sunlight) after having been in darkness, while, as was shown above, they moved away from the bulb when the latter was brought closer to the animals after they had been previously in the light. Similar responses have been noted by L. B. Clark (1931) for the insect *Dineutes*.

Although it is felt that the facts presented in this paper by no means solve the manner in which light controls the vertical movements of copepods in the sea, it is believed that they are worth while considering before the very complicated problem of phototropism be solved.

ACKNOWLEDGMENTS

The writer wishes to express his gratitude to Dr. A. G. Huntsman of the Biological Board of Canada for stimulating the investigation in many ways; also to the Biological Board of Canada, the Department of Biology of the University of Toronto, and the Woods Hole Oceanographic Institution, under whose auspices the investigation was carried out.

For criticism of the manuscript, the author feels indebted to Dr. A. G. Huntsman of the University of Toronto, and to Dr. G. L. Clarke of Harvard University and of the Woods Hole Oceanographic Institution.

LITERATURE CITED

Clark, L. B., 1931. Some factors involved in the reaction of insects to changes in luminous intensity. *Jour. Exper. Zool.*, **58**: 31.

Sars, G. O., 1903. Crustacea of Norway. Bergen Museum, 6.

Wilson, C. B., 1932. Copepods of the Gulf of Maine. *U. S. Nat. Mus. Bull.*, vol. **158**.

Clarke, G. L., 1930. Changes of phototropic and geotropic signs in *Daphnia* induced by changes of light intensity. *Jour. Exper. Biol.*, **7**: 109.

Contribution No. 185

C.-G. ROSSBY:

ON THE MUTUAL ADJUSTMENT OF PRESSURE AND VELOCITY DISTRIBUTIONS IN CERTAIN SIMPLE CURRENT SYSTEMS, II

Reprint from:
SEARS FOUNDATION: JOURNAL OF MARINE RESEARCH
Vol. 1, No. 3, September 20, 1938. Pp. 239–263, figs. 84–87.

ON THE MUTUAL ADJUSTMENT OF PRESSURE AND VELOCITY DISTRIBUTIONS IN CERTAIN SIMPLE CURRENT SYSTEMS, II

By

C.-G. ROSSBY

Massachusetts Institute of Technology
*and Woods Hole Oceanographic Institution**

In a previous report (Rossby, 1937) the author investigated certain changes in the mass distribution which accompany the slow lateral diffusion of momentum in a straight parallel current in an unlimited ocean of constant depth. The principal results of this investigation may be stated as follows:

The main stream increases slowly in width (for large times (t) it is proportional to $t^{1/4}$) while the maximum velocity in the axis of the current gradually decreases (being proportional to $t^{-1/4}$ for large values of t). If no frictional losses occur at the bottom the total *absolute* momentum of the current remains constant. The diffusion is accompanied by a slight banking to the right of the down stream direction, in such a fashion that the difference in height of the free surface between the right and the left edges of the current eventually increases by about eight per cent. Weak counter currents develop on both sides of the main stream as a result of the banking.

This analysis of the disintegration of a current system is supplemented in the present article with a study of the mutual adjustment of mass and velocity distributions in a current system which is gradually being built up by a prescribed wind system acting upon a portion of the ocean surface. The problem will be analyzed in several stages, to bring out more clearly the mechanics of the adjustment process. Frictional forces resulting from lateral mixing will be neglected in the present study but will be included in a third article to be published in a later issue of this journal.

We shall consider at first a homogeneous, incompressible ocean of constant depth D_o, which is at rest initially. Through wind action a certain amount of momentum is communicated to an infinite strip of the width $2a$. The details of the mechanism of this transfer are not important in the present connection. It is sufficient to say that the fluid column between $y = + a$ and $y = - a$ is endowed with a certain mean velocity u in the positive x-direction. The y-direction is horizontal, normal to the x-direction and points to the left from the x-direction. The momentum relative to the surface of the earth per unit length of current is then given by the expression $2\rho u_o a D_o$, ρ being the density of the water.

---

* Contribution No. 185.

This momentum (M) is associated with a Coriolis' force of the magnitude fM and directed 90° to the right of the momentum. In this expression f represents the Coriolis' parameter. As no balancing pressure gradient exists, the current will move to the right until enough of a pressure gradient has been established to check further deflection. It is the purpose of this first preliminary calculation to determine the characteristics of the final equilibrium state.

Frictional forces resulting from lateral mixing will be neglected outside the main stream. Within the stream they are assumed to maintain a laterally constant axial velocity which, however, as a result of the displacement of the current to the right must decrease during the adjustment. Since, the lateral stresses merely bring about a redistribution, not a change, of the absolute momentum, the permissibility of the above assumptions depends upon whether a significant redistribution occurs within the interval required for the adjustment process here considered. This question will be considered later.

The general character of the adjustment process is indicated by the cross section in Fig. 84, which is drawn to facilitate the understanding of the analysis but does not correspond to any actual numerical solution. If one assumes that the velocity distribution across the main stream is constant after completed adjustment, it follows that the free surface in the final equilibrium must have a constant slope within the current itself.

During the adjustment the individual fluid columns to the left of the main current shrink vertically, stretch horizontally. Let y_o represent the initial position of a given fluid vertical to the left of the main stream, y its final position. The equation of motion for the x-direction (current axis) takes the form

$$\frac{du}{dt} = fv, \tag{1}$$

there being no pressure gradient in the x-direction and no frictional force. Integration gives

$$u = f(y - y_o) = -f(y_o - y), \tag{2}$$

indicating that each fluid column on completed adjustment will move upstream at a speed proportional to its total displacement to the right.

If the final depth of a certain column is indicated by D, its initial depth by D_o, the equation of continuity takes the form

$$Ddy = D_o dy_o \tag{3}$$

or

$$D = D_o \frac{dy_o}{dy}. \tag{4}$$

After completed adjustment gradient motion prevails. Thus

$$0 = -fu - g\frac{dD}{dy}. \tag{5}$$

Combination of (2), (4) and (5) gives

$$\frac{d^2y_o}{dy^2} = \frac{y_o - y}{\lambda^2}, \tag{6}$$

where

$$\lambda = \frac{1}{f}\sqrt{gD_o}. \tag{7}$$

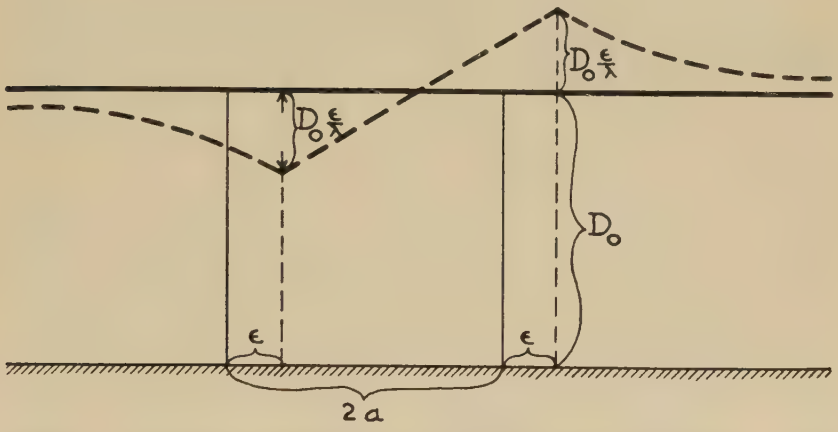


Figure 84. Schematic representation of the adjustment of mass distribution in a homogeneous ocean. See text.

A similar differential equation may be obtained for D,

$$\frac{d^2D}{dy^2} = \frac{D - D_o}{\lambda^2}, \tag{8}$$

and this equation is a special case of a more general equation

$$\frac{\partial^2 D}{\partial x^2} + \frac{\partial^2 D}{\partial y^2} = \frac{D - D_o}{\lambda^2}, \tag{9}$$

valid for arbitrary quasistatic transformations of an originally motionless incompressible fluid sheet of the initial depth D_o.* This last equation expresses the conservation of absolute vorticity.

* The term quasistatic transformation is employed here in preference to the term adiabatic transformation which is generally used in Mechanics to designate processes of this type but which would be ambiguous in meteorology and also to some extent

The length λ is a fundamental parameter in all quasistatic deformations. It is possible to define such a length also for stratified and compressible media, such as the atmosphere. In view of its great significance it seems appropriate to introduce a special name for this quantity. Its magnitude is that of the radius of the inertia circle corresponding to the velocity of long waves in a channel of the depth D_o. It is proposed to name λ the *radius of deformation.*

Integration of (6) gives

$$y_o - y = Ae^{\frac{y}{\lambda}} + Be^{-\frac{y}{\lambda}}, \tag{10}$$

A and B being arbitrary constants of integration. Since the displacement $y_o - y$ must vanish at great distances to the left from the main current (large y-values), it follows that

$$A = 0 \tag{11}$$

and thus

$$y_o - y = \varepsilon e^{-\frac{y}{\lambda}}, \tag{12}$$

ε being the total displacement to the right, of the left edge of the main stream. In this formula the y-coordinate is counted from the final position of the left edge of the main stream.

The depth of the free surface at the left edge of the current (D_l) is given by (4) and (12),

$$D_l = D_o\left(1 - \frac{\varepsilon}{\lambda}\right) \tag{13}$$

By a similar analysis it is possible to compute the rise of the free surface along the right edge of the current for an equal displacement ε to the right. The result is

$$D_r = D_o\left(1 + \frac{\varepsilon}{\lambda}\right). \tag{14}$$

The slope of the free surface across the main stream is now given by $\frac{1}{2a}(D_r - D_l)$. Thus, since gradient wind must prevail in the final equilibrium, it follows that the final mean velocity u_f of the main stream must be given by

$$u_f = \frac{g}{f}\frac{1}{2a}(D_r - D_l) = \frac{gD_o\varepsilon}{f\lambda a} = \frac{\lambda}{a} f\varepsilon. \tag{15}$$

---

in oceanography (for a definition and discussion of adiabatic transformations see for instance, A. Sommerfeld, Atombau und Spektrallinien, 3. Auflage, Vieweg, Braunschweig, 1922).

The displacement of the main stream cannot have changed its absolute momentum. This constancy is expressed by an equation derived previously (Rossby, 1937, p. 19)

$$(16) \qquad \int_{-a+\epsilon}^{a+\epsilon} D_o\,(u_o - fy)\,dy = \int_{-a}^{+a} D\,(u_f - fy)\,dy,$$

the y-coordinate on both sides of the equation being counted from the final center of the current.* Since u_o, u_f, and D_o are constants, it follows that

$$(17) \qquad 2aD_o u_o = u_f \int_{-a}^{+a} Ddy + f \int_{-a+\epsilon}^{a+\epsilon} D_o y dy - f \int_{-a}^{+a} Dydy.$$

The first integral on the left side gives the volume, which remains constant and equal to $2aD_o$. Thus

$$(18) \qquad 2aD_o\,(u_o - u_f) = fD_o \int_{-a+\epsilon}^{a+\epsilon} ydy - f \int_{-a}^{+a} Dydy.$$

The appropriate expression for D is obtained from (13) and (14). It has the form

$$(19) \qquad D - D_o = - D_o \cdot \frac{\varepsilon}{\lambda} \frac{y}{a}.$$

If this expression is substituted in (18) one finds, after some reductions,

$$(20) \qquad u_f = u_o - f\varepsilon\left(1 + \frac{a}{3\lambda}\right).$$

---

* It is of course possible to treat the adjustment of the main stream by the same exact method which was used above in treating the environment. For the main stream, equation (2) changes into

$$(2a) \qquad u = u_o - f\,(y_o - y)$$

and the differential equation (6) into

$$(6a) \qquad \frac{d^2 y_o}{dy^2} = \frac{1}{\lambda^2}\left(y_o - y - \frac{u_o}{f}\right).$$

The solution of this differential equation is

$$(10a) \qquad y_o - y = \frac{u_o}{f} + Ae^{\frac{y}{\lambda}} + Be^{-\frac{y}{\lambda}},$$

the two integrations constants A and B being needed to satisfy the requirement of continuity in displacement at the two boundaries. The over-all method used above is, however, amply sufficient for our present needs.

It is easy to verify that the product $\varepsilon\left(1+\frac{a}{3\lambda}\right)$ represents the total displacement to the right of the mass center of the current during the adjustment. If (15) and (20) are combined it follows that

$$\varepsilon = \frac{u_o}{f}\frac{1}{1+\lambda/a+a/3\lambda} \tag{21}$$

and, from (15) and (21),

$$u_f = u_o\frac{\lambda/a}{1+\lambda/a+a/3\lambda}\,. \tag{22}$$

In middle latitudes ($f = 10^{-4}\text{sec.}^{-1}$) the radius of deformation has a value of 1400 km. for a basin of 2 km. depth. If the current has a width of 200 km. (a = 100 km.) and an initial velocity of 50 cm. p. s. it follows that a displacement of one third of one kilometer would be sufficient to establish the required balancing pressure gradient. The initial velocity would be reduced by seven percent as a result of the deflection and the maximum counter current velocity on both sides of the main stream would be about 3.3 cm. p. s.

By the time the main stream reaches its equilibrium position it has acquired a finite velocity to the right and must therefore continue its displacement beyond the equilibrium point until an excessive pressure gradient develops which forces it back. An *inertia* oscillation around the equilibrium position results. It is well known that the period of such an oscillation must be half the pendulum day. The main stream will therefore reach the equilibrium position already in a few hours. From the rapidity of this adjustment it follows that large unbalanced momenta never have time to accumulate. It is probably more correct to assume that the momentum is added quasistatically, in such a fashion that each infinitesimal amount of momentum leads to a practically instantaneous adjustment of the mass distribution. Since a normal wind stress of, say, 1 dyne per cm.^{2} acting on top of a 2 km. deep water column produces a mean momentum per unit mass of less than 0.5 cm. p. s. per day it would appear that the assumption of quasistatic adjustment must be very nearly fulfilled. However, as long as the addition of momentum takes place at a variable and finite rate, a certain fraction of the energy communicated to the system will presumably always appear as an inertia oscillation. The preceding result, that changes in the stress distribution on the ocean surface necessarily must lead to inertia oscillations, was clearly recognized by Ekman in his early studies of drift currents (Ekman, 1905).

It is evident that while the frictional redistribution of momentum during the period of one inertia oscillation may be quite negligible, the total time required for the building up, through wind action, of a gradient current of the magnitude assumed above is so long that it certainly would be utterly impermissible to neglect the diffusion of momentum during this entire period.

It is next desired to investigate the effect of stratification on the process of mass adjustment. A simple case will be analyzed to bring out the nature of the modification which has to be made in the preceding analysis.

Fig. 85 is a schematic representation of the adjustment process in a two-layer ocean, the upper layer having the density ρ, the lower the density ρ'. The undisturbed thicknesses of the two layers is D_o and D_o'. It is now assumed that an infinitely long strip of the upper fluid, enclosed between the limits $y_o = a$ and $y_o = -a$, is endowed with a velocity u_o. A deflection of the current results and continues until a balancing pressure gradient has been established across the main stream.

The pressure gradients which develop in the upper layer during the adjustment must set the lower homogeneous layer in motion. However, if the latter is very deep it is possible to demonstrate that its displacements and final velocities must be fairly small. It is possible to analyze exactly the adjustment of the lower layer using the method which was applied above to the environment of the main stream in the single-layer case. This will be done later on. As a first approximation, however, it is sufficient to assume that the lower layer remains at rest; thus the deep water displacements associated with deformations of the internal boundary lead to negligibly small axial velocities. This restriction will be removed later.

If the bottom remains at rest it follows that

$$\rho D + \rho' D' = \text{constant} \tag{23}$$

and consequently

$$\frac{d}{dy}(D + D') = \frac{\rho' - \rho}{\rho'}\frac{dD}{dy} = -\frac{\rho' - \rho}{\rho}\frac{dD'}{dy}. \tag{24}$$

It is evident from (23) and (24) that the slope of the internal boundary is always proportional and opposite to the slope of the free surface, which is given by the left side in (24). The preceding analysis, including equations (2), (3) and (4), remains unchanged. The gradient current equation (5) changes into

$$O = -fu - g\frac{d}{dy}(D + D') \tag{25}$$

or, because of (24),

$$O = -fu - g\cdot\frac{\rho' - \rho}{\rho'}\frac{dD}{dy}. \tag{26}$$

Thus, if one reduces the acceleration of gravity in the proportion $\frac{\rho' - \rho}{\rho'}$ and substitutes for g a value γ, defined by

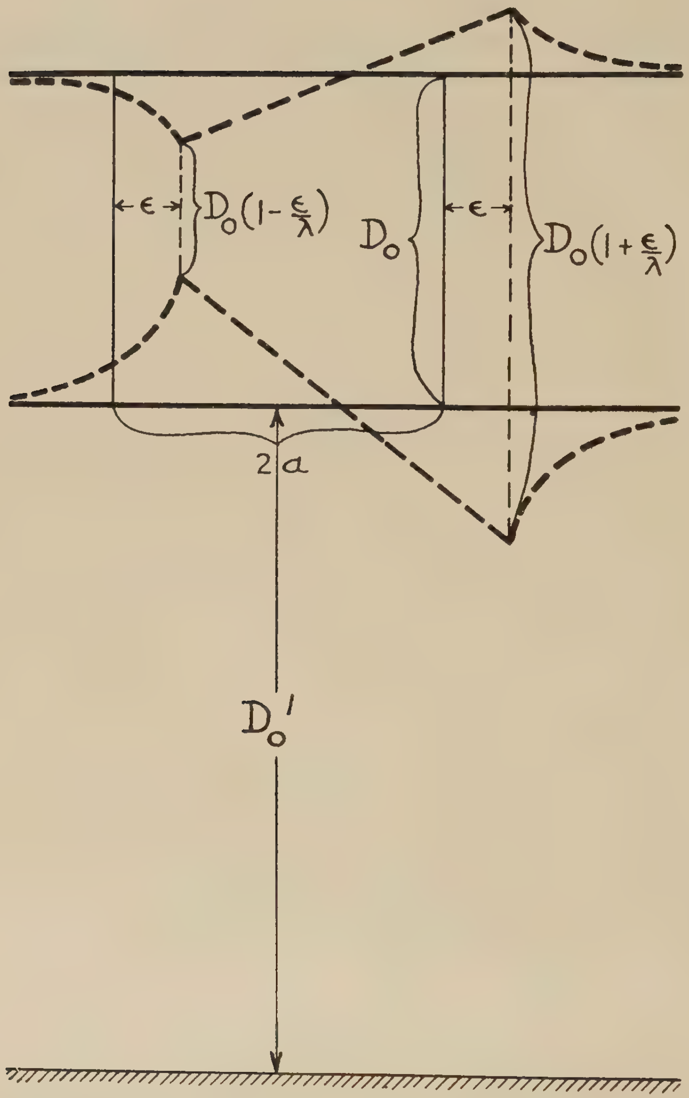

ϵ
$D_0(1-\frac{\epsilon}{\lambda})$
D_0
ϵ
$D_0(1+\frac{\epsilon}{\lambda})$
$2a$
D_0'

Figure 85. Schematic representation of the adjustment of mass distribution in a double layer ocean. See text.

$$\gamma = g \cdot \frac{\rho' - \rho}{\rho'} \tag{27}$$

all the previously derived results remain valid. The system is in every respect identical with a single-layer ocean of the depth D and subject to an acceleration of gravity of the value γ. The substitution (27) has one very important consequence. The radius of deformation, defined in (7), is now given by

$$\lambda = \frac{1}{f}\sqrt{\gamma D_o} = \frac{1}{f}\sqrt{\frac{\rho' - \rho}{\rho'} g D_o}\,. \tag{28}$$

Assuming an upper homogeneous layer with an original depth $D_o = 400$ m, and assuming a density discontinuity of 0.2 percent, it follows that

$$\lambda = 28 \text{ km.} \qquad (f = 10^{-4}\text{sec.}^{-1}).$$

The radius of deformation is thus reduced to $\frac{1}{50}$ of its original value. Assuming the same values for u and a as before, the deflection of the current will now be about 2 km. compared with the previous value of 0.33 km. The reduction in the mean speed of the current due to this deflection is greatly increased, the final axial velocity u_f having a value of about 5.3 cm. p. s. and the counter currents are correspondingly increased to about 20 cm. p. s. The radius of deformation measures that distance from either edge of the main stream in which the counter current velocity has fallen off to the fraction $\frac{1}{e}$ of its maximum value, and this distance is now reduced to $\frac{1}{50}$ of its previous value. Thus the adjustment of the mass distribution will be accompanied by the development of strong and narrow counter currents, while the corresponding currents in the homogeneous case will be very broad and extremely weak.

The preceding results suggest that the adjustment of the mass distribution in a stratified medium will be accompanied by a more intense development of inertia oscillations than the corresponding adjustment in a homogeneous medium. It is actually possible to compute the energy available for inertia oscillations by forming the difference between the total energy before and after adjustment. Such a calculation is easily made and clearly indicates that a much larger fraction of the initial energy goes into the oscillating motion in the stratified case than in the homogeneous.

It is found that the initial energy E_o, given by the expression

$$E_o = \rho a D_o \cdot u_o^2,$$

and the final energy E_f are related through the formula

$$E_f \doteq E_o \cdot \frac{\frac{\lambda}{a}}{1+\frac{\lambda}{a}+\frac{a}{3\lambda}} \tag{29a}$$

and thus the fraction of the initial energy available for inertia oscillations is given by

$$E_{oscillation} = E_o \frac{1+\frac{a}{3\lambda}}{1+\frac{\lambda}{a}+\frac{a}{3\lambda}}\,. \tag{29b}$$

This last expression is not quite correct, a small error resulting from the assumption that the velocity of the main stream is constant laterally also in the final equilibrium state. This error is not significant in the single-layer case but may be of some consequence in a stratified medium. A comparison of the two cases discussed above indicates that in the single-layer ocean only 7% of the initial energy goes into inertia oscillations, whereas in the second case the major portion of the initial energy (89%) must appear as an inertia oscillation.

Since most currents are built up through a fairly gradual addition of momentum the numerical values obtained through the suggested application of the energy integral are of small significance. Nevertheless, because of the variability of the surface stresses it appears probable that vigorous inertia oscillations must develop in stratified media and express themselves as a marked intensification of the large-scale horizontal turbulence which must develop due to the dynamic instability of the shearing zones between the current and its surrounding counter currents (Pekeris, 1938). Such intensification would not occur in homogeneous media. This tentative conclusion agrees well with Parr's suggested relationship between lateral mixing and vertical stability (Parr, 1936).

The total amount of momentum received from the wind per unit time is distributed over a much deeper column in the case of a single-layer homogeneous ocean than in the case of stratified water. Thus the initial unbalanced velocity components will be stronger in stratified than in homogeneous water and this fact would further favor the development of lateral turbulence in stratified water.

We shall next consider motions set up in the deeper of the two layers as a result of displacements and mass adjustments in the upper layer. It is assumed that no tangential stresses are transmitted through the boundary between the two strata. Originally the lower layer is at rest and characterized by a constant depth D_o'.

During the adjustment process the internal boundary will be deformed. Since continuity of mass must be preserved it follows that

$$D'dy' = D_o'dy_o', \tag{30}$$

y_o' and y' being the initial and final positions of a given fluid vertical.

The equation of motion for the x-direction is given by

$$\frac{du'}{dt} = fv' \tag{31}$$

or, after integration,

$$u' = f(y' - y_o') = -f(y_o' - y'). \tag{32}$$

It will now be assumed that wind action or other processes have led to the establishment of a known horizontal pressure gradient in the upper layer. The problem is to determine the final velocity u' in the lower layer for prescribed values of the gradient current u in the upper layer.

It is of course possible to assume that an initially unbalanced current component exists in a portion of the upper layer and to solve simultaneously the equations which describe the adjustment processes in the two layers. In this case the adjustment of the mass distribution is accomplished through a transversal circulation which, to an observer looking downstream, takes place in a clock-wise sense (see fig. 85). Such clock-wise circulations have been observed in the California current during periods of acceleration and estimates of their intensity have been made (Sverdrup, 1938). An exact solution of a problem of this type will be presented by Mr. H. Wexler and the author in a later issue of this journal. For the present we shall restrict ourselves to the case of a prescribed pressure distribution, or gradient current system, in the upper layer. If this new pressure distribution in the upper layer is applied quasistatically the solution presented below represents the final equilibrium state. If it is applied suddenly or built up at an irregular rate, inertia oscillations will appear, both above and below, superimposed upon the equilibrium state here computed.

The depth of the upper layer is D. The height of the free surface is given by $D + D'$ and thus

$$u = -\frac{g}{f}\frac{d}{dy'}(D + D'). \tag{33}$$

The gradient current equation for the lower layer takes the form

$$u' = -\frac{g}{\rho' f}\frac{d}{dy'}(\rho D + \rho' D') \tag{34}$$

or

$$u' = \frac{\rho u}{\rho'} - \frac{\gamma}{f}\frac{dD'}{dy'}. \qquad \left(\gamma = \frac{\rho' - \rho}{\rho'} g\right). \tag{35}$$

A combination of (30), (32) and (35) gives

$$\frac{d^2u'}{dy'^2} - \frac{u'}{\lambda'^2} = -\frac{\rho}{\rho'}\frac{u}{\lambda'^2}, \tag{36}$$

the radius of the deformation λ' now being given by

$$\lambda' = \frac{1}{f}\sqrt{\gamma D_o'} = \frac{1}{f}\sqrt{\frac{\rho' - \rho}{\rho'} g D_o'}\,. \tag{37}$$

If the superimposed gradient current u vanishes for $y' = \pm\,\infty$ the same must apply to u'. It then follows from (36) that u' becomes vanishingly small for very large values of λ' (great depths of the lower layer).

The deformation of the internal boundary is easily computed from (30) and (32), combined into the form

$$\frac{D' - D_o'}{D_o'} = -\frac{1}{f}\frac{du'}{dy'}, \tag{38}$$

which is an expression for the conservation of absolute vorticity in the lower layer.

If it is assumed that the upper layer was at rest before the wind stresses responsible for the gradient current u were applied, it follows that the distortion of the free surface, $h = D + D' - D_o - D_o'$, must vanish for large positive and negative values of y. Thus it follows from (33) that u must satisfy the requirement

$$\int_{-\infty}^{+\infty} u\,dy' = 0. \tag{33b}$$

If the superimposed current is symmetric with respect to y it further follows that one must have

$$\int_{0}^{\infty} u\,dy' = \int_{-\infty}^{0} u\,dy' = 0. \tag{33c}$$

One must furthermore assume that the deformation of the free surface took place in such a fashion that no mass was added or subtracted. It follows that one must require that

$$\int_{-\infty}^{+\infty} h\,dy' = \int_{-\infty}^{+\infty} (D + D' - D_o - D_o')\,dy' = 0. \tag{33d}$$

This last condition is satisfied if u is symmetric and satisfies the condition (33c).

Fig. 86 represents two velocity distributions, u and u', which satisfy equation (36). The velocity distribution in the upper layer, supposedly established through wind action, is given by

$$\frac{u}{u_m} = \left[1 - \frac{2\beta\,(1+12\beta)\,\eta^2}{1+6\beta} + \frac{8\beta^3\eta^4}{1+6\eta}\right] e^{-\beta\eta^2}, \quad (\lambda'\eta = y') \tag{39}$$

and the corresponding velocity distribution in the lower layer is then

$$\frac{u'}{u_m} = \frac{\rho}{\rho'}\,\frac{1}{1+6\beta}\,[1 - 2\beta\eta^2]\,e^{-\beta\eta^2}. \tag{40}$$

In plotting the curves for $\frac{u'}{u_m}$ and $\frac{u}{u_m}$ it was assumed that $\beta = \frac{1}{9}$.

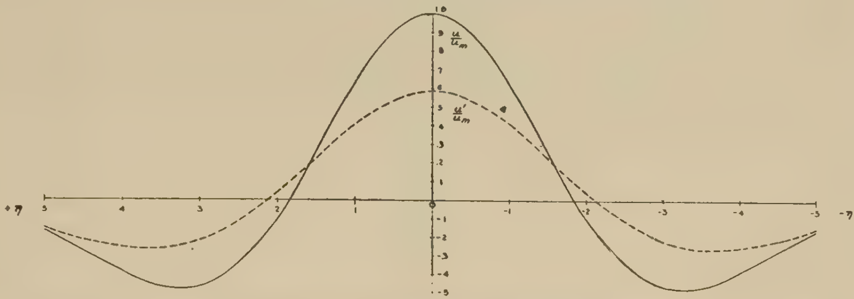


Figure 86. Example of two velocity distributions satisfying equation (36). See text.

The deformation of the internal boundary is represented in Fig. 87. It follows from (38) that the deflections of the internal boundary will be antisymmetric with respect to y'. In the particular case here investigated the equation for the internal boundary is

$$\frac{D' - D_o'}{D_o'} = \frac{\rho}{\rho'}\cdot\frac{u_m}{f\lambda'}\cdot\frac{2\beta}{1+6\beta}\,[3 - 2\beta\eta^2]\cdot\eta\cdot e^{-\beta\eta^2} \tag{41}$$

It is apparent from the solution presented above that the internal boundary adjusts itself so as to counteract, in the lower layer, the horizontal pressure gradients transmitted downward from the upper layer, *but it is also evident that this compensation is very incomplete.*

The preceding analysis raises several interesting questions. Most important of these is the following: Will the effect of deformations of the free surface be felt to some extent throughout the entire water column also in case of a continuous variation of density with depth or will the dynamically created solenoids in the interior completely cancel the effect of the surface pressure gradient? It is evident that the usefulness of "dynamic" velocity calculations of non-permanent current patterns to a very large extent depends upon the answer to this question.

We shall attempt to answer this question by a study of the following problem:

An ocean basin of uniform depth is at rest initially. The density decreases at a constant rate upward, from the value ρ_b at the bottom to the value ρ_h at the height h_o above the bottom. Above this stable layer there is a homogeneous layer of the density ρ_h. Through wind action, or in some other fashion, the free surface is deformed, and a corresponding system of gradient currents set up in the homogeneous water. How do the deep layers react to the new pressure gradients transmitted from above?

We shall assume that the deep water is made up of a very large number of layers of infinitesimal thickness, each one limited above and below by a surface of constant density. Thus each particular layer is enclosed between two isopycnic surfaces, $\rho =$ constant and $\rho + \delta\rho =$ constant. Within each layer the density may be considered constant and equal to the mean density of the layer $(\rho + \frac{1}{2}\delta\rho)$. Each layer is horizontal before the deformation sets in but is warped during the adjustment process. In the final equilibrium state *horizontal* gradient flow prevails and the motion is thus parallel to the contour lines for that particular layer.

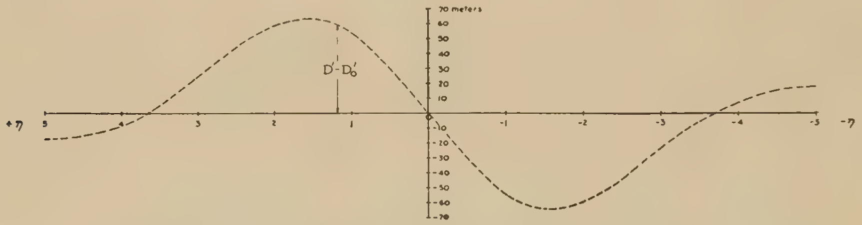


Figure 87. Deformation of the internal boundary. See text.

Now consider a chain of particles in one of these isopycnic layers. In the final stage its circulation may be computed from the circulation theorem which, in this particular case, takes the form

$$C = -f(A - A_o), \tag{42}$$

A_o being the area enclosed by the projection of the chain on a level surface before the deformation, A the corresponding area after the deformation. C is positive for cyclonic circulation.

In the final state horizontal gradient motion prevails. Thus

$$C = \oint u\delta x + v\delta y \tag{43}$$

δx and δy being the components of the horizontal projections of the line elements of the chain. It follows from Stokes' theorem that

$$C = \int\int\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)\delta x\delta y \tag{44}$$

where $\frac{\partial}{\partial x}, \frac{\partial}{\partial y}$ *now represent derivatives with respect to* x *and* y *along a constant density surface.*

The right side of equation (42) can be written in the form

$$-f\left[\int\int \delta x \delta y - \int\int \delta x_o \delta y_o\right], \tag{45}$$

the subscript *0* referring to the initial state. The equation of continuity gives

$$D = D_o \frac{\partial (x_o, y_o)}{\partial (x, y)} \tag{46}$$

D_o and D representing the vertical thickness of an individual element before and after the deformation. Thus

$$f(A - A_o) = f\int\int\left[1 - \frac{\partial (x_o, y_o)}{\partial (x, y)}\right]\delta x \delta y = f\int\int \frac{D_o - D}{D_o}\delta x \delta y \tag{47}$$

and consequently,

$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} = f\frac{D - D_o}{D_o}. \tag{48}$$

ζ is the vertical component of vorticity in the particular isopycnic sheet under study. *In the equation (48)* $\frac{\partial}{\partial x}$ *and* $\frac{\partial}{\partial y}$ *represent derivatives with respect to* x *and* y *along a surface of constant density.*

If $z\ (x, y, \rho)$ represents the height of a given isopycnic surface after adjustment, $z_o\ (\rho)$ its initial height, it follows that

$$D = -\frac{\partial z}{\partial \rho}\delta\rho, \quad D_o = -\frac{\partial z_o}{\partial \rho}\delta\rho \tag{49}$$

and thus

$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} = f\frac{\dfrac{\partial z}{\partial \rho} - \dfrac{\partial z_o}{\partial \rho}}{\dfrac{\partial z_o}{\partial \rho}}. \tag{50}$$

If one introduces a new measure for the density, defined by

$$r = \frac{\rho_b - \rho}{\rho_b - \rho_h}, \quad \rho_b - \rho_h = 2\kappa\rho_b, \quad \rho = \rho_b(1 - 2\kappa r) \tag{51}$$

it follows that

$$z_o = 0,\ z = 0,\ r = 0 \text{ for } \rho = \rho_b \tag{52}$$

$$z_o = h_o,\ z = h,\ r = 1 \text{ for } \rho = \rho_h. \tag{53}$$

The assumption is now introduced that the initial vertical density distribution is linear. Thus

(54) $$z_o = h_o r.$$

Substitution in (50) gives

(55) $$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} = f \frac{\dfrac{\partial z}{\partial r} - h_o}{h_o}.$$

If one finally introduces the symbol Δ for the vertical departure of each isopycnic surface from its initial position, the law for the conservation of vorticity reduces to the form

(56) $$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} = \frac{f}{h_o}\frac{\partial \Delta}{\partial r}, \quad \Delta = z - h_o r.$$

The hydrostatic equation must be transformed to include r instead of z as the independent variable, since otherwise the law for the conservation of vorticity cannot be effectively utilized. The pressure at a height z above the bottom is given by

(57) $$p = g\rho_h H + g \int_z^h \rho dz,$$

H being the thickness of the superimposed homogeneous layer. Integration by parts gives

(58) $$p = g\rho_h (h + H) - g\rho z - g \int_\rho^{\rho_h} z d\rho$$

or

(59) $$p = g\rho_h (h + H) - g\rho z + 2\kappa g\rho_b \int_r^1 z dr.$$

If n represents one of the horizontal coordinates (x or y) and the variation of p along a constant density surface be computed one finds

(60) $$\frac{\partial p}{\partial n} = g\rho_h \frac{\partial (h + H)}{\partial n} - g\rho \frac{\partial z}{\partial n} + 2\kappa g\rho_b \int_r^1 \frac{\partial z}{\partial n} dr.$$

The horizontal variation of any function p in the n-direction and the variation of p with n along a constant density surface are connected through the formula

(61) $$\frac{\partial p}{\partial n} = \left(\frac{\partial p}{\partial n}\right)_z + \frac{\partial p}{\partial z}\frac{\partial z}{\partial n}.$$

If p represents the pressure the above formula reduces to

$$\frac{\partial p}{\partial n} = \left(\frac{\partial p}{\partial n}\right)_z - g\rho\frac{\partial z}{\partial n}. \tag{62}$$

Thus

$$\left(\frac{\partial p}{\partial n}\right)_z = g\rho_h\frac{\partial}{\partial n}(h + H) + 2\kappa g\rho_b\int_r^1 \frac{\partial z}{\partial n}\,dr. \tag{63}$$

It follows that gradient current velocities may be computed from

$$\rho f v = g\rho_h\frac{\partial}{\partial x}(h + H) + 2\kappa g\rho_b\int_r^1 \frac{\partial z}{\partial x}\,dr \tag{64}$$

$$-\rho f u = g\rho_h\frac{\partial}{\partial y}(h + H) + 2\kappa g\rho_b\int_r^1 \frac{\partial z}{\partial y}\,dr. \tag{65}$$

Disregarding compressibility, the total percentual variation of density along a vertical in the open sea is of the order of magnitude of 0.2 percent. Thus it is entirely permissible to simplify the above equations by setting

$$\frac{\rho_h}{\rho} = \frac{\rho_b}{\rho} = 1. \tag{66}$$

Since z_o is independent of x and y one finally obtains

$$\frac{fv}{g} = \frac{\partial}{\partial x}(h + H) + 2\kappa\int_r^1 \frac{\partial \Delta}{\partial x}\,dr \tag{67}$$

$$-\frac{fu}{g} = \frac{\partial}{\partial y}(h + H) + 2\kappa\int_r^1 \frac{\partial \Delta}{\partial y}\,dr \tag{68}$$

and, for the vorticity,

$$\frac{f\zeta}{g} = \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)(h + H) + 2\kappa\int_r^1 \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)\Delta\,dr. \tag{69}$$

The vertical variation of vorticity is obtained from (69) through differentiation. The result is

$$\frac{\partial \zeta}{\partial r} = -\frac{2\kappa g}{f}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)\Delta. \tag{70}$$

Eliminating ζ between (56) and (70) one obtains

$$\boxed{\frac{\partial^2 \Delta}{\partial r^2} + \frac{2\kappa g h_o}{f^2}\left(\frac{\partial^2 \Delta}{\partial x^2} + \frac{\partial^2 \Delta}{\partial y^2}\right) = 0.} \tag{71}$$

There must be continuity in velocity and consequently also in vorticity at the boundary between the homogeneous and the stable water. It follows that ζ is prescribed for the upper boundary ($r = 1$). At the bottom $\Delta = 0$. Thus there is one solution, and one only, which satisfies the requirements of the original problem and the fundamental differential equation (71).

In the case of a parallel current system the preceding equations take a very simple form. It follows from (68) that

$$\frac{\partial u}{\partial r} = \frac{2\kappa g}{f}\frac{\partial \Delta}{\partial y} \tag{72}$$

and from (56) that

$$\frac{\partial u}{\partial y} = -\frac{f}{h_o}\frac{\partial \Delta}{\partial r}. \tag{73}$$

If one introduces the radius of deformation λ, defined by

$$\lambda^2 = \frac{2\kappa g h_o}{f^2} \tag{74}$$

it follows that

$$\frac{\partial U}{\partial r} = \frac{\partial Z}{\partial \eta} \tag{75}$$

$$\frac{\partial U}{\partial \eta} = -\frac{\partial Z}{\partial r}\left(y = \lambda\eta,\ U = \frac{u}{f\lambda},\ Z = \frac{\Delta}{h_o}\right). \tag{76}$$

Thus U and Z are conjugate functions, satisfying the equations

$$\left(\frac{\partial^2}{\partial r^2} + \frac{\partial^2}{\partial \eta^2}\right)U = 0,\ \left(\frac{\partial^2}{\partial r^2} + \frac{\partial^2}{\partial \eta^2}\right)Z = 0. \tag{77}$$

The boundary conditions are:

$$Z = 0 \text{ for } r = 0. \tag{78}$$

$$U \text{ prescribed for } r = 1. \tag{79}$$

The rate at which the current velocity decreases downward is well illustrated by the following case:

The superimposed velocity in the homogeneous layer is given by

$$u_{hom} = u_m \cos k\eta \tag{80}$$

This represents a system of parallel currents of alternating direction, the "wave-length" L being given by

$$L = \frac{2\pi\lambda}{k},\ k = \frac{2\pi\lambda}{L}. \tag{81}$$

The corresponding velocity distribution in the interior is given by

$$u = u_m \cdot \frac{e^{kr} + e^{-kr}}{e^{k} + e^{-k}} \cos k\eta, \tag{82}$$

and the deformation of the individual density surfaces may be computed from

$$\Delta = \frac{h_o}{f\lambda} u_m \cdot \frac{e^{kr} - e^{-kr}}{e^{k} + e^{-k}} \sin k\eta. \tag{83}$$

The velocity at the bottom (u_b) is given by

$$\frac{u_b}{u_m} = \frac{\cos k\eta}{\cosh k} \tag{84}$$

and the maximum bottom velocity by

$$\frac{u_{b\,max}}{u_m} = \frac{1}{\cosh k} = \frac{1}{\cosh \frac{2\pi\lambda}{L}} \tag{85}$$

Thus the effect of the superimposed velocity gradients will extend to greater depths or, which is the same, be more marked at the same depth for a longer "wave-length" L than for a shorter.

The ratio (85) between the maximum bottom velocity and the maximum gradient current velocity has been computed for different values of $n = \frac{L}{\lambda}$. Assuming $h_o = 1800$ m., $2\kappa = 2 \cdot 10^{-3}$, $g = 10^3$ cm. sec.$^{-2}$, $f = 10^{-4}$ sec.$^{-1}$, one finds

$$\lambda = 60 \text{ km.}$$

The resulting values are given in the line marked $\frac{K_o}{h_o} = 0$ in table I.

It is evident from these values that the redistribution of mass within a single 1800 m. deep layer of uniform stability is insufficient to reduce a superimposed horizontal surface pressure gradient to zero at the bottom It appears that for a current width of 240 km. ($L = 480$ km., $n = 8$) the maximum bottom velocity will still be 75% of the maximum gradient velocity of the surface layer. If the total density range and the depth of the stable layer are doubled the value of λ is doubled. The appropriate value of n is reduced to 4, but the maximum bottom velocity is still 40% of the maximum surface velocity. There is no reason to expect such high velocities near the bottom and thus the question concerning the equalization of the horizontal pressure gradients at great depths remains open.

In a further effort to settle this question we shall finally investigate if the presence of another, deep homogeneous layer below the stable water plays an important role in the cancellation of surface pressure gradients through redistribution of mass. It will be assumed that the deep water has a constant density ρ_b and an undisturbed depth K_o. Then, if Δ_o represents the deformation of the surface separating the lower homogeneous layer from the stable water above, it follows from the conservation of vorticity in the lower layer and from the requirement of continuity in the velocity distribution that

$$\left(\frac{\partial u}{\partial y}\right)_{r=0} = -\frac{f\Delta_o}{K_o} \tag{88}$$

or,

$$\left(\frac{\partial U}{\partial \eta}\right)_{r=0} = -\frac{h_o}{K_o} \cdot Z_{r=0}. \tag{89}$$

The solution corresponding to the boundary condition (80) and the revised boundary condition (89) is

$$\frac{u}{u_m} = \frac{h_o \cosh kr + kK_o \sinh kr}{h_o \cosh k + kK_o \sinh k} \cos k\eta \tag{90}$$

and

$$\frac{\Delta}{h_o} = \frac{u_m}{f\lambda} \frac{h_o \sinh kr + kK_o \cosh kr}{h_o \cosh k + kK_o \sinh k} \sin k\eta. \tag{91}$$

For $K_o = 0$ these equations become identical with (82) and (83) and for $K_o \to \infty$ the solution reduces to

$$\frac{u}{u_m} = \frac{\sinh kr}{\sinh k} \cos k\eta \tag{92}$$

$$\frac{\Delta}{h_o} = \frac{u_m}{f\lambda} \frac{\cosh kr}{\sinh k} \sin k\eta. \tag{93}$$

The relation between the maximum velocity in the homogeneous bottom layer and the maximum velocity in the homogeneous surface layer is now obtained by setting $r = 0$ in (90). The result is

$$\frac{u_{b\,max}}{u_m} = \frac{1}{\cosh k\left(1 + \frac{kK_o}{h_o} \tanh k\right)} = \frac{1}{\cosh \frac{2\pi\lambda}{L}\left(1 + \frac{2\pi\lambda}{L} \cdot \frac{K_o}{h_o} \tanh \frac{2\pi\lambda}{L}\right)} \tag{94}$$

For $K_o = 0$ this formula reduces to the one derived previously (85) and for $K_o \to \infty$ the ratio becomes zero, i. e. the bottom layer will then be at rest. For an initial depth of the lower homogeneous layer of 1800 m. and for the same value of n as before ($n = 8$, $L = 480$ km.) the maximum bottom velocity will still be 50% of the maximum gradient velocity in the upper layer.

TABLE I

$\frac{K_o}{h_o}$ n	0.5	1	2	4	8	16
0	.0000	.0037	.0862	.399	.755	.928
0.5	.0000	.0009	.0337	.232	.605	.855
1	.0000	.0005	.0277	.162	.499	.809
2	.0000	.0003	.0119	.103	.372	.774
∞	0	0	0	0	0	0

The preceding analysis indicates that the effect on the deep water of pressure gradients transmitted from above will be considerably reduced through redistribution of mass in the interior of the ocean, but with reasonable values for the depth and for the total vertical density range there is always a considerable residual effect even in the homogeneous bottom layer. One must conclude that a changing pressure applied on a horizontal surface near the sea surface will be felt also in the bottom water and thus must produce, at least temporarily, sizeable stratospheric currents.

It is obvious that this conclusion does not apply to cases of steady state motion in the ocean, since various frictional forces then have the opportunity to dissipate the kinetic energy of the stratospheric currents. However, the so-called permanent wind systems which actuate the superficial layers of the ocean are changing from day to day and from season to season. It is the author's definite opinion that these changing wind systems must produce deformations of the ocean surface and consequently horizontal pressure gradients which, in the light of the preceding analysis, necessarily must set also the deepest strata in motion. There is no justification whatsoever for the point of view which pictures the ocean stratosphere as completely inert apart from the slow thermal circulation produced by the production of bottom water through cooling in the Antarctic.

SUMMARY

The principal purpose of this investigation is to study those changes in the internal mass distribution which accompany the initial establishment of oceanic current systems through wind stresses applied at the sea surface. Whenever surface water is set in motion through wind action, horizontal pressure gradients are established in the uppermost layers of the ocean. Surrounding and underlying water masses which are not acted upon by the wind, will be set in motion by these new pressures. If, as a first approximation, frictional forces are neglected outside the body of water which is directly influenced by the wind, the displacements and final equilibrium of the surrounding masses may be determined from the requirement that each individual element of water must retain its absolute vorticity. The final equilibrium thus determined is one of dynamic equilibrium, i.e. characterized by steady motion.

The total energy (potential and kinetic) of the final equilibrium is normally less than the initial energy (kinetic energy received from the wind). The difference goes into inertia oscillations around the final equilibrium state computed from the vorticity theorem mentioned above.

The specific results may be stated as follows:

1. If, through wind action, an infinite strip of water in an initially motionless homogeneous ocean basin is set in motion in the direction of its own axis, the entire current filament will be deflected to the right of the downstream direction* as a result of the initially unbalanced Coriolis' force associated with its momentum. The sea surface will rise along the right edge, fall along the left edge, until a transversal pressure gradient (slope) is established which exactly balances the Coriolis' force. The rise (drop) of the sea surface in the environment of the current may be computed from the requirement that each vertical column of water must conserve its absolute vorticity.

2. The sum of the potential and kinetic energy in this equilibrium state is somewhat less than the initial kinetic energy of the system (there is no potential energy in the initial state). The difference in energy goes into an inertia oscillation with a period of twelve pendulum hours. As a result of this inertia oscillation the deflection of the current will proceed beyond the equilibrium position and then reverse direction. However, in a homogeneous ocean the fraction of energy stored in this inertia oscillation is small.

3. If, through wind action, an infinite strip of water in the upper of two homogeneous layers is set in motion in the direction of its own axis, a similar adjustment process occurs. While the free surface rises along the right edge, sinks along the left edge of the current, the internal boundary

---

* On the northern hemisphere.

will be deformed in the opposite sense. If the lower layer is very deep it is permissible to assume that it will be practically motionless also after completed adjustment. The ratio of the deformation of the free surface to that of the internal boundary then has the same value as the ratio of the difference in density between the two layers to the density of the upper layer. In this case the total deflection of the current system is increased several times over the corresponding deflection in a homogeneous ocean.

4. In such a double-layer ocean with a resting bottom layer the fraction of the initial energy which goes into inertia oscillations is many times larger than in a homogeneous ocean.

5. The adjustment to equilibrium of the initially unbalanced current filament is in both cases accompanied by the development of counter currents in the environment. These counter currents are very weak and broad in the case of a homogeneous ocean but narrow and intense in the case of a double-layer ocean.

6. The shear zones between the current and its environment are known to be dynamically unstable and should therefore have a tendency to break up into large-scale horizontal eddies (lateral turbulence).

7. Since there is a much greater supply of energy available for vigorous inertia oscillations in a double-layer ocean than in a homogeneous ocean, it is reasonable to assume that lateral turbulence must be more strongly developed in stratified than in homogeneous water; this conclusion strongly supports Parr's suggestion concerning the relation between lateral eddy viscosity and vertical stability.

8. In a stratified ocean the momentum received from the wind will be distributed over a shallow vertical column, whereas it will be spread over a much deeper column in homogeneous water. For this reason strong unbalanced current components are more likely to occur in stratified than in homogeneous water. This would tend to produce stronger inertia oscillations, and hence presumably stronger lateral turbulence, in stratified water than in homogeneous, again in agreement with the suggested relationship between lateral turbulence and vertical stability.

9. If the lower of the two layers in the idealized ocean referred to above has a finite depth, the displacement of the upper unbalanced current towards its equilibrium position will be accompanied by a transversal displacement of the lower layer in the opposite direction. This displacement below will, as a result of the Coriolis' acceleration, lead to the development of a gradient current in the lower layer in the same direction as the initial current in the upper layer. Thus, although the internal boundary between the two layers is deformed in such a fashion as to counteract the pressure gradients associated with the deformations of the free surface, it may be stated that it is normally impossible to superimpose a horizontal pressure gradient at the

ocean surface without having its effect temporarily transmitted all the way to the bottom layer.

10. This result is further analyzed in the case of an ocean consisting of an upper, homogeneous layer and a lower stable layer with an initially linear density distribution. It is assumed that a prescribed horizontal pressure distribution (perturbation pressure) is established in a geopotential surface within the upper homogeneous layer. Assuming that each infinitesimal isopycnic layer in the stable water conserves its absolute vorticity, it is possible to determine the final equilibrium state. It is found that sizeable gradient currents normally must develop also next to the bottom.

11. The percentual rate at which a prescribed perturbation pressure at the surface is equalized with increasing depth in an ocean basin of normal stability depends upon the lateral dimensions of the superimposed perturbation. A superimposed gradient current system in the upper homogeneous layer with a width of a few kilometers will hardly be felt at the bottom of the stratified layer (assumed to have a depth of 1800 m), but if the superimposed current has a width of between two and three hundred kilometers the horizontal pressure gradient at the bottom will still be about one half of the surface pressure gradient.

12. If there is a deep layer of homogeneous water also below the stable layer the gradient currents next to the bottom will be further reduced, but it still appears that sizeable gradient currents must develop in the bottom water whenever the horizontal pressure distribution in the homogeneous water near the surface changes over reasonably wide areas.

13. The preceding conclusions regarding the motion of the bottom water do *not* apply to a perfectly steady state of motion in the ocean. However, since the large atmospheric wind systems which drive the ocean circulation change from day to day and from season to season it is permissible to state with a reasonable degree of assurance, that it is entirely inappropriate to consider the homogeneous bottom water as inert beyond the slow thermal circulation maintained by antarctic cooling.

14. It is in particular injustifiable to assume à priori that the velocity distribution within larger non-permanent current patterns (such as the larger of those eddies which form intermittently along the edges of the permanent current systems) may be computed on the basis that there is no motion in the deep water.

REFERENCES

1. **Ekman**, V. W.

1905. On the Influence of the Earth's Rotation on Ocean-Currents, Arkiv. für Matematik, Astronomi och Fysik, Bd. 2, No. 11.

2. **Parr**, A. E.

1936. On the Probable Relationship between Vertical Stability and Lateral Mixing Processes, Journal du Conseil, Vol. XI, No. 3.

3. **Pekeris**, C. L.

1938. Wave Disturbances in a Homogeneous Current, Transactions of the American Geographical Union, Vol. XX.

4. **Rossby**, C.-G.

1937. On the Mutual Adjustment of Pressure and Velocity Distribution in Certain Simple Current Systems, Journal for Marine Research, Vol. I, No. 1.

5. **Sverdrup**, H. U.

1938. On the Process of Upwelling, Journal for Marine Research, Vol. I, No. 2.

Contribution No. 186

Über die ganz- und halbtägige Mondkomponente der internen Wellen im westlichen Nordatlantischen Ozean.

Von **H. R. Seiwell**, Woods Hole, Massachusetts.

Beitrag Nr. 186, Woods Hole Oceanographic Institution.

Im Vorsommer des Jahres 1937 bestätigte eine zweite Untersuchung der internen Wellen im westlichen Nordatlantischen Ozean [an einem Ort ungefähr 100 Sm NzW von Bermuda] die früheren Befunde[1]), daß große senkrechte Verschiebungen [im Betrage von 50 m und mehr] der Wassersäule in diesem Gebiet innerhalb kurzer Zeitdauern stattfinden. Den Berechnungen der senkrechten Bewegungen lagen zwei Serien von Temperaturmessungen — zwischen der Oberfläche und einer Tiefe von 1200 bis 1300 m — zugrunde, die ununterbrochen während zweier Perioden von 53 Stunden (Gruppe A) bzw. 93 Stunden (Gruppe B) vorgenommen wurden. Die vorliegende Diskussion bezieht sich nur auf die 24- und 12-Mondstunden-Periode der senkrechten Bewegung; die Feststellung der Amplituden und Phasen erfolgte in der Weise, daß die Daten der harmonischen Analyse unterzogen und die Koeffizienten nach der Methode der kleinsten Quadrate berechnet wurden. Da die ursprünglichen Temperaturangaben darauf hinwiesen, daß große Teile der Diskontinuitätsschicht senkrecht wie eine homogene Masse oszillieren, wurden Kombinationen von Isothermen, wie in Tab. 1 gezeigt, in der Analyse verwendet.

Tabelle 1.

Isotherme	**Gruppe A.**
19°—20°	$H = 127.3 + 1.05 \cos \frac{2\pi}{24}(t - 5.38^h) + 0.94 \cos \frac{2\pi}{12}(t - 7.24^h)$
18°	$H = 312.3 + 4.91 \cos \frac{2\pi}{24}(t - 9.50^h) + 3.23 \cos \frac{2\pi}{12}(t - 1.68^h)$
17°	$H = 638.1 + 6.91 \cos \frac{2\pi}{24}(t - 18.31^h) + 3.20 \cos \frac{2\pi}{12}(t - 11.13^h)$
14°—16°	$H = 758.5 + 6.02 \cos \frac{2\pi}{24}(t - 20.91^h) + 4.89 \cos \frac{2\pi}{12}(t - 9.57^h)$
13°	$H = 848.1 + 4.18 \cos \frac{2\pi}{24}(t - 19.47^h) + 4.74 \cos \frac{2\pi}{12}(t - 10.40^h)$
11°—12°	$H = 915.0 + 0.72 \cos \frac{2\pi}{24}(t - 15.11^h) + 3.76 \cos \frac{2\pi}{12}(t - 11.29^h)$
8°—10°	$H = 1019.1 + 1.97 \cos \frac{2\pi}{24}(t - 23.52^h) + 2.53 \cos \frac{2\pi}{12}(t - 0.23^h)$
7°	$H = 1124.1 + 3.11 \cos \frac{2\pi}{24}(t - 22.05^h) + 2.51 \cos \frac{2\pi}{12}(t - 10.63^h)$
6°	$H = 1201.5 + 2.87 \cos \frac{2\pi}{24}(t - 21.36^h) + 4.22 \cos \frac{2\pi}{12}(t - 11.43^h)$
	Gruppe B.
19°—20°	$H = 125.0 + 3.28 \cos \frac{2\pi}{24}(t - 18.21^h) + 1.48 \cos \frac{2\pi}{12}(t - 2.69^h)$
18°	$H = 292.9 + 8.16 \cos \frac{2\pi}{24}(t - 21.76^h) + 13.16 \cos \frac{2\pi}{12}(t - 10.99^h)$
17°	$H = 613.3 + 19.31 \cos \frac{2\pi}{24}(t - 5.08^h) + 8.18 \cos \frac{2\pi}{12}(t - 8.63^h)$
14°—16°	$H = 722.5 + 10.09 \cos \frac{2\pi}{24}(t - 5.68^h) + 4.45 \cos \frac{2\pi}{12}(t - 11.96^h)$
13°	$H = 824.3 + 14.28 \cos \frac{2\pi}{24}(t - 11.24^h) + 4.37 \cos \frac{2\pi}{12}(t - 8.16^h)$
11°—12°	$H = 933.8 + 4.24 \cos \frac{2\pi}{24}(t - 10.64^h) + 4.16 \cos \frac{2\pi}{12}(t - 11.85^h)$
8°—10°	$H = 1047.9 + 0.59 \cos \frac{2\pi}{24}(t - 7.19^h) + 2.47 \cos \frac{2\pi}{12}(t - 7.89^h)$
7°	$H = 1143.2 + 3.82 \cos \frac{2\pi}{24}(t - 8.16^h) + 3.76 \cos \frac{2\pi}{12}(t - 7.98^h)$
6°	$H = 1217.2 + 3.78 \cos \frac{2\pi}{24}(t - 2.74^h) + 7.48 \cos \frac{2\pi}{12}(t - 8.49^h)$

---

[1]) Short period vertical oscillations in the western basin of the North Atlantic. H. R. Seiwell, Papers in Physical Oceanography and Meteorology. Vol. V. No 2.

Die beiden Serien zusammenhängender Temperaturbeobachtungen (Gruppe A: 23^h, 19. Juni bis 4^h, 22. Juni; Gruppe B: 8^h, 24. Juni bis 5^h, 28. Juni) von der „Atlantis"-Station 2887 [34° 1′ N, 65° 56′ W] sind getrennt analysiert worden; die Phasen sind als Mondstunden nach dem Meridiandurchgang (Greenwich-Meridian) angegeben. Die 24-Mondstunden-Komponente, der M_1-Gezeiten-Komponente entsprechend, ist wahrscheinlich hauptsächlich die Resultante von K_1 [Mond-Sonnentide] und O_1 [Mondtide], also von Komponenten mit Geschwindigkeiten von 23.93 bzw. 25.82 Sonnenstunden, während der 12-Mondstunden-Bestandteil von der lunaren halbtägigen Hauptkomponente M_2 beherrscht zu werden scheint, aber auch die Wirkungen der halbtägigen Hauptsonnenkomponente S_2 [Geschw. 12 Sonnenstunden] und ebenfalls die Wirkungen der größeren halbtägigen Mondkomponente N_2 [Geschw. 12.06 Sonnenstunden] einschließen kann. Die Beobachtungsdauer war nicht genügend lang, um mögliche Wirkungen dieser Partialkomponenten abzusondern (Tab. 1).

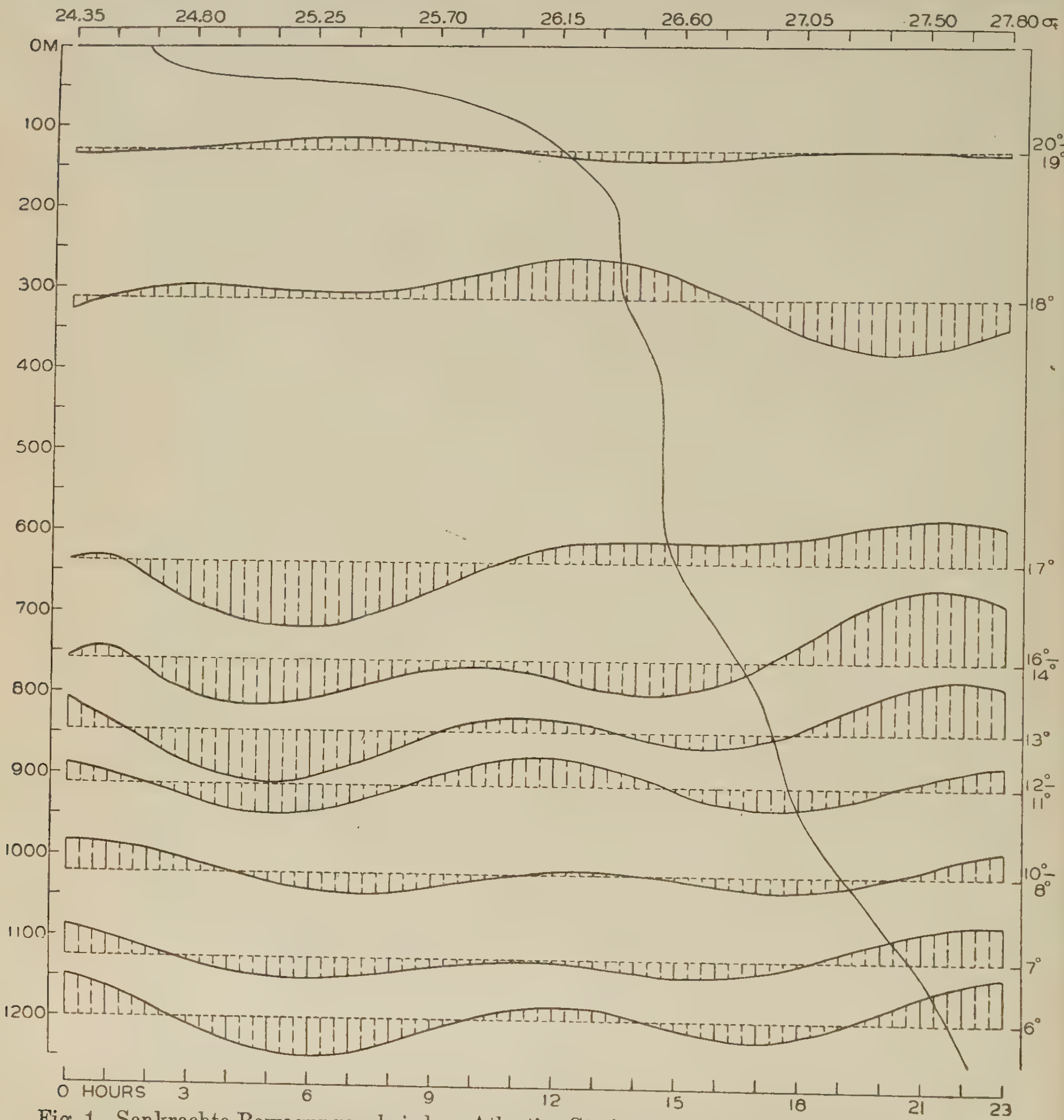


Fig. 1. Senkrechte Bewegungen bei der „Atlantis"-Station 2887 [23^h, 19. Juni bis 4^h, 22. Juni; 60° Zeit] als Folge der vereinten Wirkung von 12- und 24-Mondstunden-Wellen.

Die Mondzeit ist auf der unteren Abszisse vermerkt; an der linken Ordinate sind die Tiefen angegeben. Die Skala der senkrechten Verlagerung weicht von der Tiefenskala insofern ab, als der Maßstab der vertikalen Änderung der Lage der Isothermen 8.33mal größer ist als der links angegebene Tiefenmaßstab. Die Dichte ist ausgedrückt in $\sigma_t = (\varrho - 1.00000) \times 10^3$ und ihre vertikale Verteilung während der Beobachtung durch eine stärkere Linie angedeutet.

Die vereinte Wirkung der 24- und der 12-Mondstunden-Komponente für Gruppe A — siehe Fig. 1 — veranschaulicht die größten Verlagerungen, die in der permanenten Diskontinuitätsschicht — an der Verteilung der Dichte gezeigt — vorkommen. Diese sind in der Oberflächenschicht weniger ausgesprochen; innerhalb der dichtesten Teile der Sprungschichten werden Minimumverlagerungen in annähernd 1000 m Tiefe beobachtet. Eine Folge der senkrechten Veränderungen in Phase und Amplitude ist die ununterbrochene Schrumpfung und Dehnung der Wassersäule: waagerechte und senkrechte Geschwindigkeiten addieren sich zu den durchschnittlichen Geschwindigkeiten.

Die Ergebnisse der Analysen von Gruppe A und B deuten auf eine zeitliche Veränderung der senkrechten Verteilung der Amplitude und Phase, und zwar sowohl der 24- als auch der 12-Stunden-Komponente; die Amplituden zur Zeit der Beobachtung in Gruppe B waren gelegentlich mehr als dreimal so groß wie die in Gruppe A gefundenen. Jedoch zeigen beide Konstantengruppen dieser Station im allgemeinen bezeichnende Ähnlichkeiten, die darauf hinweisen, daß fortschreitende Wellen von ähnlicher Beschaffenheit vorhanden waren und daß die beobachtete Wirkung teilweise unmittelbar aus der Struktur der Wassersäule resultiert. Man darf nicht erwarten, daß Phasen und Amplituden kurzperiodischer Wellen an irgendeiner Stelle im Ozean lange Zeit hindurch konstant bleiben, wie es vielleicht der Fall sein könnte bei sehr langperiodischen stehenden Wellen, sofern solche in unserem Untersuchungsbereich überhaupt vorkommen.

Es ist wahrscheinlich, daß Arbeiten über die internen Wellen der ozeanischen Becken künftig für physikalisch-ozeanographische Forschungen besondere Bedeutung erlangen werden, und zwar nicht nur wegen der Erscheinung an sich, sondern vor allem auch wegen ihrer störenden Wirkungen auf dynamische Berechnungen, wie sie für die Ermittlung der Geschwindigkeiten und des Wassertransportes durchgeführt werden. Eine ausführlichere Behandlung dieser Befunde ist in Vorbereitung.

Sonderabdruck aus den Annalen der Hydrographie und Maritimen Meteorologie
1938, Heft X, S. 485 bis 487.

Ernst Siegfried Mittler und Sohn, Buchdruckerei, Berlin SW 68.

Contribution No. 188

THE OCCURRENCE AND DISTRIBUTION OF NITRIFYING BACTERIA IN THE SEA

By

CORNELIA L. CAREY

*Woods Hole Oceanographic Institution,**

and

Barnard College, Columbia University

Of all the phases in the cycle of nitrogen in the sea perhaps that of the oxidation of ammonia has received the most attention, and yet many questions related to this process are still unsettled. Evidences of nitrifying bacteria have been found in marine bottom materials, particularly in shallower waters, but their presence in the water and plankton of the ocean has not been established.

An attempt was made, therefore, to try to ascertain (1) whether sea water itself with no added source of nitrogen could produce nitrite and nitrate, and (2) whether there were any regions of the ocean other than the ocean floor where such bacteria were present, and nitrifying processes were taking place.

METHODS

Samples of sea water were collected from different stations and kept in the laboratory in sterile flasks for several weeks, at room temperature and in the dark. These were tested at various intervals for the presence of nitrite, nitrate, and in some cases for ammonia. Other samples of sea water were held at 80° C. for 30 minutes, and after they had absorbed sufficient oxygen again they were inoculated with different samples of fresh marine muds or with plankton. Standard sea water medium, known to be favorable for the formation of nitrites and nitrates was also inoculated with fresh marine bottom material, sea water, or plankton. This medium contained 10 g. sand, 1 g. $CaCO_3$, 40 cc. sea water, 5 mg. K_2HPO_4, and 5 mg. $(NH_4)_2SO_4$ per flask. For nitrate formation, the $(NH_4)_2SO_4$ was replaced by 5 mg. KNO_2. These cultures were also incubated at room temperature and in the dark.

Tests for nitrite were made with diethly-alpha-naphthylamine reagent. In testing for nitrate any nitrite present was first destroyed by keeping the solution, to which sulphanilic-acetic acid solution had been added in a bath of boiling water for 20 minutes, and then testing for nitrate with diphenyl amine reagent. Portions of all solutions treated in this manner were always

---

* Contribution No. 188.

Reprint from SEARS FOUND. JOURN. MAR. RES.

tested again after heating to see if all nitrite had been destroyed. The nitrate test is not as sensitive as that used for nitrite. Therefore, the former cannot be detected in as small amounts by this means. The presence of ammonia was determined by using Nessler's solution in spot plates. All test tubes and pipettes used for testing for nitrite and nitrate, were washed and rinsed several times in tap and then distilled water and steamed before using.

PRESENCE OF NITRIFYING BACTERIA IN BOTTOM MATERIALS AND IN SEA WATER. MUD SAMPLES IN STERILE STANDARD MEDIA

In order to determine whether organisms contained in bottom material would oxidize ammonia to nitrite and the latter to nitrate, samples of mud were taken for the first experiment, 1 mile W. by N. of Woepecket Buoy in Buzzards Bay at a depth of 14.3 meters. The fresh mud was added to sterile standard media. This experiment was repeated using sand collected off Quissett Harbor, Buzzards Bay, at a depth of 9.1 meters. The results showed that Woepecket mud produced nitrite from ammonia in 2 days, while the nitrite thus produced was oxidized to nitrate in 35 days. Similar oxidation of the nitrite occurred in the nitrite medium. The sand, however, did not give a positive test for nitrite for 11 days. Nitrite appeared in this culture after 69 days, but no nitrate was found in the medium originally containing nitrite.

To amplify this experiment and determine more definitely the locus of nitrification a series of mud cores were obtained off Nomans Land. These cores were about 5–6 inches long. Standard media were inoculated with portions of these cores. One flask of each medium received fresh sea water taken from above the core, and two other flasks both surface mud and water directly over the core. Portions of the core at a depth of 1, 5, 10 or 12.5 centimeters were also placed in these media. (Table I.) All flasks containing ammonium sulphate medium and inoculated with mud showed the production of nitrite in 9 days or less, with the exception of the sample taken at a depth of 12.5 cm. below the surface of the mud. The nitrite increased with time so that in 30 days or less all of the cultures containing the mud inocula were showing strong tests for nitrite, except the last sample. Material taken from another core at a depth of 10 cm. gave decided nitrite tests. The media inoculated with mud and water, or with water alone were much slower in giving positive tests, and when such tests occurred they were weak. Nitrate did not appear in the nitrite medium for 2 months. After that, positive tests were obtained in the cultures inoculated with mud, but not in those receiving water, or mud and water. This corroborates previous findings, that nitrites and nitrates are produced from muds in cultures when given a supply of ammonia or nitrite respectively (Waksman, Hotchkiss, and Carey (*24*)).

MUD SAMPLES IN STERILE SEA WATER WITH NO ENRICHMENT

Top and bottom layers of other cores obtained off Nomans Land were inoculated into sterile sea water. The water, after heating to 80° C., was placed in the refrigerator to become resaturated with oxygen; it was then inoculated with the mud samples. The cultures were tested for ammonia, nitrite, and nitrate with continuously negative results up to 53 days.

TABLE I

Production of Nitrite and Nitrate from Profile of Mud Collected off Nomans Land at Depth of 31.1 Meters

	NITRITE								*NITRATE*
	Incubation, Days								*Inc. Days*
	3	*6*	*16*	*22*	*30*	*44*	*64*	*99*	*99*
a) Nitrite Medium									
1. Water above core	0	0	0	0	0	0	†	†	0
2. Surface mud and water	0	0	0	0	0	0	tr.	††	0
3. Core, 1 cm. deep	0	0	††	††††	†††††	†††††	†††††	0	†
4. Core, 5 cm. deep	0	tr.	†	††††	†††††	†††††	†††††	0	††††
5. Core, 12.5 cm. deep	0	0	0	0	0	0	0	*	
6. Control	0	0	0	0	0	0	†	†	
b) Nitrate Medium									
1. Water above core	0	0	0	0	0	0	0	0	
2. Surface mud and water	0	0	0	0	0	0	0	0	
3. Core, 1 cm. deep	0	0	0	0	0	tr.	††	†††	
4. Core, 5 cm. deep	0	0	0	0	0	0	†	†	
5. Core 12.5 cm. deep	0	0	0	0	0	0	††	†	
6. Control	0	0	0	0	0	0	0	0	

* Discarded after 64 days.

tr. = trace, † = positive test, †† = fair, ††† = good, †††† = very good, ††††† = abundant.

Samples of mud bottom taken off Gay Head were added to 100 cc. portions of sterile sea water, as well as the water directly over the core. None of these gave any positive tests for ammonia, nitrite, or nitrate even after 53 days incubation at room temperature. This material gave positive tests for nitrite in 14 and 16 days, and for nitrate in 63 and 64 days, when inoculations were made into standard media as shown in Table I. Negative results were also obtained when "cultured" sea water, i.e., sea water which had stood for 5 days in the laboratory and had been resaturated with oxygen, was inoculated with mud and sand collected in Buzzards Bay near Woepecket Island at a depth of 9.1 meters although incubated for 59 days.

Samples of the same material gave positive tests when inoculated into standard media.

These experiments show that the presence of ammonia and nitrite-oxidizing bacteria can be demonstrated under certain experimental laboratory conditions.

To confirm this, in a second series of experiments mud from Gay Head and Buzzards Bay was added to sterile sea water and also to standard media. The depths at which these bottom samples were taken ranged from 14 to 34.7 meters. Odd numbers in the table indicate the surface layers, and even numbers the deeper layers of the core. No positive tests were obtained in the sterile water even after 52 days. In the standard medium nitrite appeared in small amounts after 5 days, and at 52 days or possibly sooner, the nitrite was being oxidized to nitrate (Table II). At the end of 90 days all the nitrite had disappeared. Complete oxidation to nitrate in the medium originally containing ammonia probably occurred before this time, but tests were not made between 52 and 90 days. Nitrate appeared in the nitrite containing medium in one case in 30 days, and in all flasks at 90 days. This again proves that enriched cultures favor production of nitrite and nitrate when inoculated with mud, whereas sterile sea water inoculated with mud does not give this reaction in the same incubation period.

To test the presence of nitrifying bacteria at greater distances from land 500 cc. portions of water obtained by the "Atlantis" from Station 2895 at depths of 10, 35, 90, 130 and 200 meters was used. Three series of flasks were prepared, one receiving fresh sea water alone; the second being enriched with 10 mg. $(NH_4)_2SO_4$, and the third containing 20 cc. of fresh sea water and 40 cc. of standard medium containing $(NH_4)_2SO_4$. The flasks were placed in the dark and tested at various intervals for ammonia, nitrite and nitrate. Nitrite and nitrate were negative up to 44 days, and tests for ammonia were positive only where this substance had been added to the water. Mud samples obtained from Station 2895 (lat. 40° 04′, long. 70° 50′) and inoculated into standard media showed, in a few cases, slight traces of nitrite after 2 weeks, but no nitrate up to 86 days. These nitrite tests, however, were only faint and not sufficient to warrant the assumption that ammonia oxidizing bacteria were present in the muds.

Similar results were obtained from bottom samples taken from greater depths, 1137–4000 meters, at latitudes of 40° 04′ to 40° 25′, and longitudes 67° 46′ to 66° 00′.

NITRIFICATION IN PLANKTON MATERIAL

In the first experiments, 10 cc. of concentrated diatom tow from Vineyard Sound was added to 250 cc. of fresh sea water containing 5 mg. K_2HPO_4 per liter. This was put into a sterile flask containing a little sterile sand.

TABLE II

PRODUCTION OF NITRITE AND NITRATE IN STANDARD MEDIA BY BOTTOM SAMPLES TAKEN OFF GAY HEAD AND IN BUZZARDS BAY

LOCATION AND DEPTH OF BOTTOM MATERIAL	NITRITE								NITRATE							
	Incubation, Days								*Incubation, Days*							
	5	*7*	*14*	*24*	*30*	*37*	*52*	*90*	*90*	*5*	*7*	*24*	*30*	*37*	*52*	*90*
1. Gay Head 5¼ mi. W. by S. ¼ S. Depth 32.9 M. Top	0	0	tr.	†††††	††	†††††	††††	0	†††	0	0	0	†	†	††	††
2. Gay Head 5¼ mi. W. by S. ¼ S. Depth 32.9 M. Bottom	0	ft. tr.	†	††	†††	†††	†††	0	†††	0	0	0	0	0	††	†††
3. Gay Head ½ mi. S. ½ E. of 1. Depth 34.7 M. Top	0	0	0	tr.	tr.	tr.	†††	0	tr.	0	0	0	0	0	tr.	††
4. Gay Head ½ mi. S. ½ E. of 1. Depth 34.7 M. Bottom	ft. tr.	ft. tr.	†	†	†††	†††††	tr.*	0	†	0	0	0	0	0	0	0
5. Buzzards Bay 2 mi. W. N. W. Woepecket Rock. Depth 14.3 M. Top	†	††	†††	†††††	†††††	†††††	†††††	0	††	0	0	0	0	0	0	†
6. Buzzards Bay 2 mi. W. N. W. Woepecket Rock. Depth 14.3 M. Bottom	tr.	tr.	††	†††	††††	†††	0**	0	†	0	0	0	0	0	0	tr.
7. Buzzards Bay 1 mi. N. W. by W. Woepecket Rock. Depth 14.6 M. Top	†	†	††	††††	††††	†††	**v.f.tr.	0	††	0	0	0	0	0	0	tr.
8. Buzzards Bay 1 mi. N. W. by W. Woepecket Rock. Depth 14.6 M. Bottom	tr.	tr.	†	††	†††††	††††	0*	0	†	0	0	0	0	0	0	0
9. Buzzards Bay ⅓ mi. N. Woepecket Rock. Depth 14.0 M. Top	††	††	†††	††††	†††††	†††††	0**	0	††	0	0	0	0	0	0	†
11. Buzzards Bay 1 mi. N. Gong 6. Depth 14.6 M. Top	tr.	†	††	†††	†††††	†††††	†††††	0	††	0	0	0	0	0	†	tr.
14. Buzzards Bay Buoy 42. Depth 33.8 M Bottom	0	0	tr.	†	††	††	†††	0	††	0	0	0	0	0	0	††
15. Control	0	0	0	0	0	0	0	0	†	0	0	0	0	0	0	0

* = Nitrate †; ** = Nitrate †††; Ft. tr. = faint trace, tr. = trace, † = positive test, †† = fair, ††† = good, †††† = very good, ††††† = abundant.

The control flask contained no plankton. These flasks were incubated in the dark. Nitrite appeared after 20 days, and became very strongly positive, while ammonia decreased and finally gave no test. No nitrate was produced up to 64 days. The controls all remained negative.

Another series of flasks were set up using unfiltered fresh sea water from Woods Hole, a little sand, and 5 mg. K_2HPO_4 per liter. Two hundred and fifty cc. portions of this water were put into each flask. Two flasks were inoculated with 10 cc. of concentrated diatom tow collected from Woods Hole or Vineyard Sound. The plankton consisted largely of *Rhizoselenia* and some *Guinardia*. In about 4 days ammonia was found in the flask inoculated with the sample of tow from Woods Hole. The ammonia in the flask increased for a time, and in 2 weeks nitrite appeared and became very strong after 29 days, when the ammonia test became negative. The flask inoculated with tow from Vineyard Sound, gave the same results, but produced ammonia more slowly. Nitrate was not present in either flask up to 29 days.

A third series of flasks was set up using, in one case, standard medium for the production of nitrite, and in the other case the same medium without ammonium sulphate. These were inoculated with 0.5 cc. of concentrated diatom tow. Ammonia was soon found in the flask containing tow and no ammonium sulphate. Nitrite appeared in both flasks, more rapidly, however, in the flask containing only plankton as a nitrogen source, but after 13 days they each gave equally positive tests. With no added ammonia the nitrite test did not finally become as strong, and after 27 days it disappeared; this was probably due to its utilization by other organisms, as no tests for nitrate were obtained up to 43 days. The flask with 5 mg. $(NH_4)_2SO_4$ showed decidedly positive tests for nitrite (3+) even up to 43 days. No nitrate was produced in this flask either. The controls were negative throughout.

Following these experiments plankton tow was collected from three different stations and added to sterile sea water. Tests were made at different intervals for nitrite, nitrate and ammonia. The first sample was taken from Vineyard Sound between Woods Hole and Tarpaulin Cove, and consisted almost entirely of copepods, a very few diatoms being present. Two tenths, 0.5, 1.0, 2.0, and 5.0 cc. of tow were added to 100 cc. portions of water. When tested 2 days after inoculation by the spot plate test ammonia was present increasing in concentration with the increase in the amount of plankton added. Nitrite first appeared in the flask containing the smallest amount of tow after three weeks. After 27 days the flasks receiving 0.5 and 1.0 cc. portions of the tow showed nitrite, and after 44 days a trace was present in the 2 cc. amount (Table III). Up to 94 days no nitrite had appeared in the flask containing 5 cc. of tow. No nitrate appeared in any culture up to 94 days. As the nitrite increased in the cultures

TABLE III

PRODUCTION OF AMMONIA AND NITRITE IN STERILE SEA WATER ON ADDITION OF COPEPOD TOW FROM VINEYARD SOUND

Flask No.	Plankton cc.	AMMONIA											NITRITE											NITRATE		
		Incubation, Days											Incubation, Days											Inc. Days		
		2	11	15	20	23	27	32	44	52	74	94	2	11	15	20	23	27	32	44	52	74	94	2	74	94
1	0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0.2	†	††	†	†	†	†	0	0	0	0	0	0	v.f. tr.	tr	†	†††	††††	†††††	†††††	††††	†††††	††††	0	0	0
3	0.5	††	†††	††	††	††	††	††	†	†	†	†	0	0	0	0	0	†	††	††††	††††	††††	††††	0	0	0
4	1.0	†††	†††	††	††	††	††	††	††	††	†	††	0	0	0	0	0	†	†††	†††††	†††††	†††††	†††††	0	0	0
5	2.0	††††	††††	††††	††††	††††	††††	†††	†††	†††	††	††	0	0	0	0	0	0	0	tr.	tr.	†	††	0	0	0
6	5.0	†††††	†††††	†††††	†††††	†††††	†††††	†††††	†††††	††††	††††	†††	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Medium contained 100 cc. sterile sea water with varying amounts of copepod tow. v.f.tr. = very faint trace, tr. = trace, † = positive test, †† = fair, ††† = good, †††† = very good, ††††† = abundant.

the ammonia decreased. The nitrite test became very strong in the cultures as they became older. Apparently nitrite producing organisms must have been present in the tow, and the decomposition of the copepods furnished the ammonia necessary for the oxidation to nitrite. If this ammonia is produced in too large quantities it retards the production of nitrite. Five drops of this tow were added to flasks of standard media for the production of nitrite and nitrate. Decided tests for nitrite were obtained in 27 days, but no nitrate was produced up to 95 days.

Tow was collected by the "Asterias" (Table IV) by towing 5 minutes with a No. 20 mesh net 10 miles northeast of Chatham. This tow consisted largely of Dinoflagellates, *Ceratium tripos,* and *Ceratium fuscus* as well as a few copepods. The tow was concentrated by filtering, and added to standard medium not containing any ammonium sulphate in the following amounts: 2, 5, 10 drops and 1.0 cc. Ammonia was present when the tow was first tested, namely 4 days after it was obtained, and nitrite appeared in the flask containing 2 drops of tow after 6 days, while after 8 weeks it was present in all flasks in small amounts, except in the flask containing 1.0 cc. of tow. At this time the ammonia had largely disappeared. The nitrite continued to increase up to 79 days. However, no nitrate was formed.

TABLE IV

PRODUCTION OF NITRITE IN STANDARD MEDIUM WITHOUT AMMONIUM SULPHATE BY DINOFLAGELLATE TOW

Flask No.	*Plankton*	*AMMONIA*							*NITRITE*							*NITRATE*			
		Incubation, Days							*Incubation, Days*							*Inc., Days*			
		4	*6*	*9*	*16*	*28*	*57*	*79*	*4*	*6*	*9*	*16*	*28*	*57*	*79*	*4*	*28*	*57*	*79*
1	Control	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	2 drops	†	†	†	0	0	0	0	0	tr.	†	†	†	†	††	0	0	0	0
3	5 drops	†	†	†	†	tr.	0	0	0	0	0	0	0	†	††	0	0	0	0
4	10 drops	††	††	††	††	††	tr.	0	0	0	0	0	0	†	††	0	0	0	0
5	1 cc.	††	††	††	††	††	†	tr.	0	0	0	0	0	0	††	0	0	0	0

Tr. = trace, † = positive test, †† = fair, ††† = good, †††† = very good, ††††† = abundant.

Tow collected by the "Atlantis" at 100 meters depth, Station 2895 lat. 40° 04′, long. 70° 50′, off the Continental Shelf contained large amounts of copepods and other animal forms, very few diatoms and a considerable bacterial population, by the time it was received in the laboratory. This concentrated tow was also added to 100 cc. portions of sterile sea water in the following amounts: 2, 5, and 10 drops, and 1.0 cc. Ammonia was present from the beginning of the experiment, decreasing with time, but no nitrite appeared up to 70 days. Neither was there any nitrate produced up to 100 days, when this tow was inoculated into standard media without ammonium sulphate, although plenty of ammonia was produced from the decomposition of the copepods. The ammonia gradually disappeared without the production of nitrate, but very small amounts of nitrite were formed after 100 days.

The lack of production of nitrite in the copepod tow from Station 2895 is difficult to account for. This tow was collected off the Continental Shelf and at a depth of 100 meters. It may be that the reason that nitrification takes place in the tow from Vineyard Sound and off Chatham is that there is more mixing of the water, so that nitrifying organisms from the bottom get into the plankton layer and the presence of ammonia in sufficient amounts from the decomposition of the plankton permits of nitrification. Since it is difficult to demonstrate the presence of these organisms in the water mass as a whole, it is possible that they may come to inhabit this particular layer because of some peculiar fitness of the environment there. There must be some ammonia produced here due to the decomposition of the dead cells in the plankton, and this may be the reason for their presence. It would seem that they must multiply in this layer, or at least be more plentiful there than in the rest of the water. If they are merely the result of the mixing of the water, or of washing in from land, one would think that on enriching and incubating other parts of the water mass, it would be possible to demonstrate their presence. It is, of course, also possible that still longer incubation periods are necessary to show the presence of these organisms.

DISCUSSION

The presence of nitrifying bacteria in sea water, their origin, the particular part of the sea they inhabit, and the role they play, has long been a matter of uncertainty. In 1899, Vernon (*22*), while studying the marine organisms of the Gulf of Naples, suggested that nitrification in the sea might be due to bacteria. Brandt (*2, 3, 4, 5, 6* and *7*) believed that he had proved the presence of these organisms when he obtained nitrification in marine muds in the presence of ammonium salts. Neither Gran (*9, 10*) nor Nathansohn (*17*) were able to obtain similar results in either the Gulf of Naples or Norwegian waters, but Gran obtained positive results from bottom material near shore. These two investigators concluded that the nitrifying organisms were brought in from land. Thomsen (*20, 21*) suggested that the absence of organisms in the sea water was due to the fact that sea water contained only traces of ammonia, while bottom material, due to the decomposition of plant and animal remains, contained greater concentrations of this compound. Brandt, on the other hand, argued that if nitrate came into the sea from the atmosphere or from land by way of the rivers and streams, etc., one would expect to find the highest nitrate content in the upper layer of the water rather than in the deeper. This is contrary to actual findings, and therefore, he concluded that nitrates must be made in the sea bottom. Thomsen was able to demonstrate the presence of nitrifying bacteria in the sea bottom, but failed to find them in the sea water, plankton, or on fixed algae. He obtained nitrification in Kiel Fjord and in the Bay of Naples near land. Nitrates were only produced from samples taken near land. Issatchenko (*14, 15*) found nitrifying bacteria in bottom material from the Arctic Ocean and Black Sea, but could not find them in surface waters. Neither could Berkeley (*1*) nor Lipman (*16*) find nitrifying forms in sea water, even after several months incubation. Lipman considered calcareous sand favorable for this oxidation process. Issatchenko also believed that sandy bottoms were more favorable for it.

Harvey (*11, 12, 13*) found that the quantity of nitrate in the English Channel was closely related to the production of phytoplankton, so that when the phytoplankton was at its maximum, nitrate was very low. In certain cases he obtained an increase of nitrate on storing. He concluded that sea water near the bottom contained nitrate producing bacteria. Rakestraw (*18, 19*) found a maximum of nitrate in August in the Gulf of Maine at about 40 meters depth. Nitrite was found to increase immediately after the summer growth period. Variations of nitrite in amount and distribution apparently depend on the season and the mixing of the water.

The findings in the present paper substantiate the previous results obtained by Carey and Waksman, and Waksman *et al* (*8, 22, 24*), where nitrite and nitrate were found to be produced from bottom samples, in the presence of an adequate nitrogen supply, and not in water under the same conditions. Nitrate was also produced from the same material but more slowly than nitrite. No attempt was made at that time to determine whether the plankton layer might contain bacteria responsible for nitrite and nitrate production.

Nitrite is an intermediate stage in the oxidation of ammonia to nitrate. Diatoms are known (ZoBell (*25*)) to reduce nitrate to nitrite, whereas the nitrifying bacteria build up nitrite and nitrate from ammonia. Various marine bacteria are able to reduce nitrate to nitrite, or ammonia or even to atmospheric nitrogen. Therefore, the mere finding of nitrite in sea water does not tell the manner of its formation.

Ammonia is the product of decomposition of the dead plankton cells. It is produced in sufficient amounts to provide a menstruum for considerable oxidation by the nitrite organisms. The amount of ammonia present in the culture determines the rapidity with which it is oxidized. With only a small amount of plankton added to each flask, only a small amount of ammonia was produced and the oxidation occurred quickly, but with larger amounts of plankton the production of nitrite was considerably retarded.

It is difficult to explain why nitrite-forming bacteria are found in some plankton masses and not in others. The plankton which gave positive tests for nitrite was collected near shore in relatively shallow places. Collection from deeper water, off the Continental Shelf, given only slight nitrite tests. The occurrence of nitrifying organism in the plankton layer may be due to vertical mixing in the shallow regions, whereby such organisms might be brought into the upper layers of the water; or it is possible that they may multiply in the layer being very sparsely distributed throughout the sea. It is, of course, possible that such organisms may be washed in from land, and thus get into the plankton near shore. The fact that they do occur in certain plankton masses and not in others, together with the fact that this may be another locus for these organisms is of interest and warrants further study.

In the experiments reported in this paper, it was found that nitrite and nitrate were produced from samples of marine bottom in considerable amounts, when these samples were taken near land. Less nitrite was produced by similar samples taken from deep water. Nitrate was not formed by the latter samples, and its production in all cases was slower than that of nitrite.

Sea water alone apparently cannot produce nitrite or nitrate, at least in the time allowed in these experiments (52 days). It is possible, however, that nitrifying organisms are present throughout the mass of sea water, but in much fewer numbers than in the sea bottom or plankton. If this is the case, it would require a much longer period of time in the laboratory, using sea water only, for such organisms to build up sufficient amounts of nitrite and nitrate from the small amounts of ammonia present in sea water, but under natural conditions and over long periods this would add a considerable amount of nitrate to the sea.

The addition of diatom or copepod plankton to sterile sea water caused the production of nitrite, when such samples were collected near land. Plankton collected farther out, off the Continental Shelf, was apparently less active, perhaps due to the lack of mixing of the water. No nitrate was produced in plankton under any conditions.

These observations lead one to conclude that nitrifying organisms are found in marine bottoms, and that by mixing of the water they may be brought into the plankton layer, where by virtue of the death and decomposition of the plankton, ammonia is liberated which these organisms may then oxidize. The lack of rapid nitrite formation in plankton off the Continental Shelf would lead to the conclusion that fewer nitrifying organisms are present there, due perhaps to lack of vertical mixing of the water. If the organisms in such a plankton are exceedingly few, a longer time of incubation would be required to determine their presence.

SUMMARY

1. Bottom material produced nitrite when inoculated into standard media. This was later oxidized to nitrate. The time required to accomplish these oxidations varied with the sample. Nitrate production was in all cases slower than that of nitrite.

2. Bottom material produced nitrate from nitrite in standard sea water media.

3. Water directly above the mud produced nitrite, but much more slowly then the mud itself, only traces being found after two months. No nitrate was produced from water over cores after three months incubation.

4. Bottom samples which produced nitrite and nitrate in standard media failed to do so in sterile sea water containing no added ammonia or nitrite salts, even after an incubation of 52 days.

5. Water samples collected away from land at depths of 10, 35, 90, 130, and 200 meters failed to produce nitrite after 44 days even when inoculated into standard media, or when enriched with ammonium sulphate.

6. Samples of mud from great depths produced nitrite very slowly and in exceedingly small amounts, and no nitrate in the time allotted to this experiment (i.e., 86 days).

7. Concentrated diatom tow collected from Woods Hole and Vineyard Sound and inoculated into sea water containing phosphate and sterile sand produced ammonia which was oxidized to nitrite, but no nitrate in 29 days.

8. Concentrated diatom tow added to sterile standard media with and without ammonium salts also caused the production of nitrite but no nitrate in 43 days.

9. Concentrated copepod tow from Vineyard Sound inoculated into sterile sea water in varying amounts gave decided production of nitrite. The greater the amount of tow added to the flasks, the longer was the time of appearance of the nitrite. The latter was produced at the expense of the ammonia, which decreased in amount as the nitrite increased.

10. Nitrite was also produced in standard media by copepod tow from Vineyard Sound. No nitrate was formed after three months incubation.

11. Dinoflagellate plankton, when inoculated into sterile standard media without ammonium sulphate, produced ammonia and nitrite, but neither substance was produced in as large amounts as in the copepod tow, probably due to the higher nitrogen content of the latter. No nitrate was produced from this plankton.

12. Copepod tow collected off the Continental Shelf at a depth of 100 meters and inoculated in varying amounts into sterile sea water and standard media without ammonium sulphate produced considerable ammonia and only very slight traces of nitrite after a long period of incubation.

The writer is indebted to Dr. Selman A. Waksman for his kindly interest and advice.

BIBLIOGRAPHY

1. Berkeley, Cyril
1919. A Study of Marine Bacteria, Straits of Georgia, B. C., Trans. Roy. Soc. Canada. 13: (V) 15–43.

2. Brandt, K.
1904. Ueber die Bedeutung der Stickstoffverbindungen für die Produktion im Meere. Bot. Centrbl. Beih., 16: 383–402.

3. Brandt, K.
1899. Ueber den Stoffwechsel im Meere. Wiss. Meeresunters. Kiel, N. F., 4: 213–331.

4. Brandt, K.
1902. Ueber den Stoffwechsel im Meere. II. Wiss. Meeresunters. Kiel, N. F., 6: 23–79.

5. Brandt, K.
1920. Ueber den Stoffwechsel im Meere. III. Wiss. Meeresunters. Kiel, N. F., 18: 185–429.

6. Brandt, K.
1922. Ueber den Stoffwechsel im Meere. Wiss. Meeresunters. Kiel, N. F., 19: 251–253.

7. Brandt, K.
1925. Stickstoffverbindungen im Meere. I. Wiss. Meeresunters. Kiel, N. F., 20: 203–292.

8. Carey, Cornelia L. and Waksman, Selman A.
1934. Presence of Nitrifying Bacteria in Deep Seas. Science, 79: 349–350.

9. Gran, H. H.
1903. Havets Bakterien og deres Stofskifte. Naturen. Bergen., 27: 33–40: 72–84.

10. Gran, H. H.
1912. Pelagic Plant Life. From Murray and Hjort, The Depths of the Ocean., London., 307–386.

11. Harvey, H. W.
1926. Nitrates in the Sea. Jour. Mar. Biol. Assoc., 14: 71–88.

12. Harvey, H. W.
1928. Nitrates in the Sea. II. Jour. Mar. Biol. Assoc., 15: 183–190.

13. Harvey, H. W.
1928. Biological Chemistry and Physics of Sea Water., Cambridge University Press.

14. Issatchenko, B. L.
1908. Zur Frage von der Nitrifikation in den Meeren. Centrbl. Bakt., II, 21: 430.

15. Issatchenko, B. L.
1926. Sur le Nitrification dans les Mers. Compt. Rend. Acad. Sci. Paris., 182: 185–186.

16. LIPMAN, C. B.
1922. Does Nitrification Occur in Sea Water? Science, 56: 501–503.

17. NATHANSOHN, A.
1906. Ueber die Bedeutung vertikaler Wasserbewegungen für die Produktion des Planktons im Meere. Abh. Matt. Phys. Kl., Kgl. Sachs. Ges. Wiss., 29: 355–441.

18. RAKESTRAW, NORRIS W.
1933. Studies on the Biology and Chemistry of the Gulf of Maine. I. Chemistry of the Waters of the Gulf of Maine, August 1932. Biol. Bull. 64: 149–158.

19. RAKESTRAW, NORRIS W.
1936. The Occurrence and Significance of Nitrite in the Sea. Biol. Bull., 71: 133–167.

20. THOMSEN, P.
1907. Ueber das Vorkommen von Nitrobakterien im Meere. Ber. Deut. Bot. Gesell., 25: 16–22.

21. THOMSEN, P.
1910. Ueber das Vorkommen von Nitrobakterien im Meere. Wiss. Meeresunters., Kiel, N. F., II: 1–27.

22. VERNON, H. M.
1899. The Relation between Marine Animals and Vegetable Life. Mitt. Zool. Sta. Neapel., 13: 341–425.

23. WAKSMAN, SELMAN A., REUSZER, H. W., CAREY, CORNELIA L., HOTCHKISS, MARGARET AND RENN, C. E.
1933. Studies on the Biology and Chemistry of the Gulf of Maine. III Bacteriological Investigations of the Sea Water and Marine Bottoms. Biol. Bull., 64: 183–205.

24. WAKSMAN, SELMAN A., HOTCHKISS, MARGARET, CAREY, CORNELIA L.
1933. Marine Bacteria and their Role in the Sea. II Bacteria concerned in the Cycle of Nitrogen in the Sea. Biol. Bull., 65: 137–167.

25. ZOBELL, C. E.
1935. The Assimilation of Ammonium Nitrogen by *Nitzschia closterium* and other Marine Phytoplankton. Proc. Nat. Acad. Sci., 21: 517–522.

Contribution No. 189

PRELIMINARY REPORT OF THE PHYTOPLANKTON OF THE GULF OF MAINE

LOIS C. LILLICK

▼

Reprinted from
"THE AMERICAN MIDLAND NATURALIST"
Vol. 20, No. 3, pp. 624-640, November, 1938

The University Press
Notre Dame, Ind.

Preliminary Report of the Phytoplankton of the Gulf of Maine[1]

Lois C. Lillick

A detailed survey of the biology of the offshore waters of the Gulf of Maine was made under the direction of Dr. A. C. Redfield by the Woods Hole Oceanographic Institution in 1933 and 1934, during which time the institution's research ketch "Atlantis" made frequent cruises into the gulf. There was no botanist associated with the laboratory at that time, but phytoplankton collections were made and stored in the hope that some one would be found to carry on this phase of the survey. In the summer of 1936 the writer undertook to work up the material, and the present paper is the resulting account of the phytoplankton.

The investigation was undertaken while the writer was a research fellow at the Woods Hole Oceanographic Institution and a student at the University of Michigan. During the past year an exchange fellowship from the University of Michigan to Radcliffe College has made possible the completion of the work. Much assistance and guidance during the course of the investigation has been received from Professor Wm. Randolph Taylor of the University of Michigan and the Marine Biological Laboratory, Woods Hole, and Professors H. B. Bigelow and A. C. Redfield of Harvard University and the Woods Hole Oceanographic Institution, for all of which the writer is deeply indebted. This paper comprises but a preliminary report. A more detailed account is in the process of preparation.

Collections were begun in September, 1933 and were made nearly every month thereafter until July, 1934. Water bottle samples were taken at 1, 10, 30, 50, and 80 meters depth. In addition net hauls were made in April and May, 1934, and August, 1936. Cruises were spaced farther apart than is desirable, but in spite of this, there is good evidence that none of the major phases of the phytoplankton cycle were missed. Both qualitative and quantitative analyses of the material were made, the results of which are best expressed in tabular form.

In Tables 1 to 3 are given lists of all species found during the survey, together with their seasonal occurrence. A great number of species in widely separated groups were represented in the phytoplankton collections. The importance of the diatoms overshadowed that of all other classes as it normally does in these latitudes. Of this group 25 genera and 69 species and varieties were identified, though the total number now known for the gulf exceeds this considerably. The Dinophyceae, of which 11 genera and 44 species were found, were of secondary importance. As yet the taxonomic work on this group has not been completed, therefore this number will probably be

---

[1] Papers from the Department of Botany of the University of Michigan No. 673; Contribution No. 189 of the Woods Hole Oceanographic Institution.

increased. Of lesser consequence are the Chrysophyceae, represented by the Silicoflagellata and Coccolithophoridaceae, the Myxophyceae, and certain unclassified flagellates. In making taxonomic determinations the following authorities were used: Bacillariophyceae, Gran (1908), Hustedt (1930 et seq.); Dinophyceae, Paulsen (1908), Lebour (1925), Schiller (1931); Coccolithophoridaceae, Schiller (1930); and Silicoflagellata, Gemeinhardt (1930). The terminology used by Fritch (1935) has been followed.

For the quantitative determinations the precipitation method developed by Nielsen and von Brand (1934) was followed. April, May and August results are based upon corrected vertical net tows rather than water bottle samples, in which cases the quantity of plankton is expressed as the number of cells found under one tenth of a square meter of surface, an area selected because it approximates that of the net used. It is not practical to publish here all the tables obtained, therefore those given (Tables 4 to 37) are ones selected from representative parts of the gulf at the different seasons. The approxi-

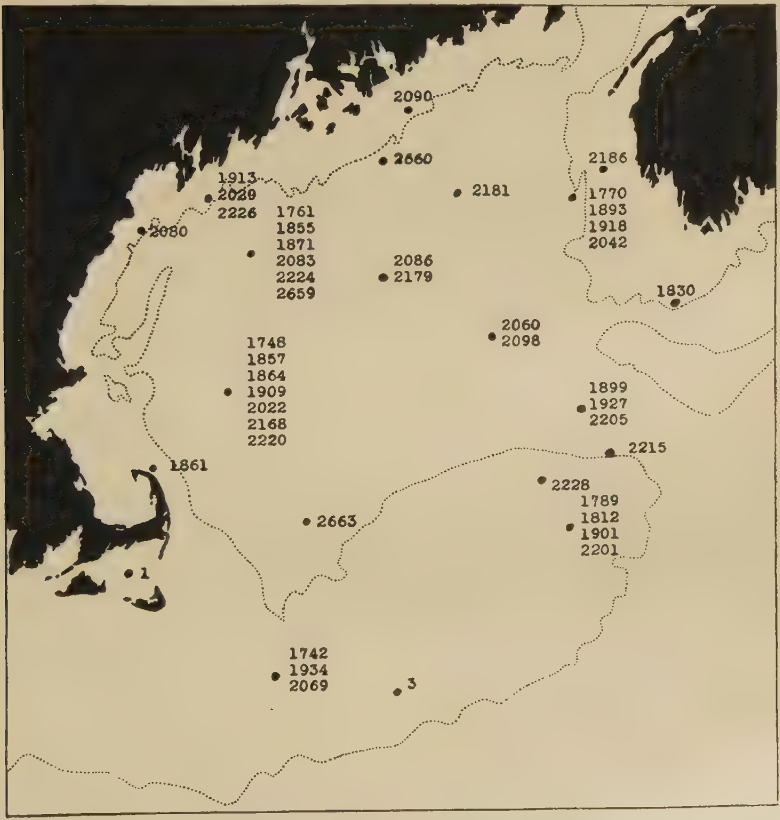

2090
2660
2186
1913
2029
2226
2181
1770
1893
1918
2042
2080
1761
1855
1871
2083
2224
2659
2086
2179
1830
2060
2098
1748
1857
1864
1909
2022
2168
2220
1899
1927
2205
2215
1861
2228
1789
1812
1901
2201
2663
1
1742
1934
2069
3

Fig. 1. Approximate locations of "Atlantis" stations in the Gulf of Maine, 1933-1934.

mate locations of the stations for which tables are given are shown in Fig. 1.

From both the quantitative and qualitative charts it can be seen that the phytoplankton of the Gulf of Maine follows the cycle that is typical of boreal seas. There is an intense flowering of diatoms in the spring, followed by a summer lull. Late in summer a minor diatom flowering arises, quickly succeeded by the scant winter population. All discussion of the significance of these data is being reserved for the more detailed account.

REFERENCES

Fritch, F. E. 1935—The structure and reproduction of the Algae. I. xvii + 791. Cambridge, England.

Gemeinhardt, K. 1930—Silicoflagellatae. Rabenhorst's Kryptogamenflora Deutschlands, Österreichs, und der Schweiz **10**(2):1-87. Leipzig.

Gran, H. H. 1908—Diatomeen. K. Brandt u. C. Apstein, Nordisches Plankton **19**:1-146. Kiel u. Leipzig.

Hustedt, F. 1930—Die Kieselalgen. Rabenhorst's Kryptogamen-flora Deutschlands, Österreichs, und der Schweiz **7**(1). Leipzig.

Lebour, M. V. 1925—The dinoflagellates of northern seas. Plymouth.

Nielsen, E. S. and Th. v. Brand. 1934—Quantitative Zentrifugenmethoden, zur Planktonbestimmung. Cons. Perm. int. pour Explor. de la Mer. Rapp. et Proc. Verb. **59**:99-100.

Paulsen, O. 1907—Peridiniales. K. Brandt u. C. Apstein, Nordisches Plankton **18**:1-116. Kiel u. Leipzig.

Schiller, J. 1930—Coccolithineae. Rabenhorst's Kryptogamen-flora Deutschlands, Österreichs, und der Schweiz **10**(2):89-273. Leipzig.

———1931—Dinoflagellates. Ibid. **10**(3). Leipzig.

Table 1

Bacillariophyceae	No. of Stations at which present								
	Sept.	Oct.	Dec.	Jan.	March	April	May	June	August
No. of stations made	11	7	8	10	11	73	48	6	11
Achnanthes taeniata Grun.	_	_	_	_	_	17	1	_	_
Actinoptychus undulatus (Bail.) Ralfs	1	1	1	1	1	_	2	1	1
Biddulphia aurita (Lyngbye) Breb. et Godey	_	_	_	_	_	9	3	_	_
Cerataulina Bergoni Per.	_	_	_	1	_	_	_	_	_
Chaetoceros spp.	1	1	_	_	1	7	_	_	_
Ch. affinis Laud.	_	_	_	_	_	37	4	_	3
Ch. atlanticus Cleve	_	_	_	_	_	19	6	_	2
Ch. borealis Bail.	_	_	_	_	1	1	1	_	1
Ch. borealis var. *concavicornis*	_	_	_	_	_	5	10	_	_
Ch. compressus Laud.	_	_	_	_	_	2	1	_	1
Ch. constrictus Gran	_	_	_	_	_	28	9	_	_
Ch. convolutus Castr.	_	_	_	_	_	44	10	_	_
Ch. debilis Cleve	_	_	_	_	1	29	9	_	_
Ch. decipiens Cleve	_	_	_	1	1	19	15	3	4
Ch. diadema (Ehr.) Gran	_	_	_	_	_	33	2	_	_
Ch. didymus Ehr.	_	_	_	_	_	19	10	_	1
Ch. furcellatus Bail.	_	_	_	_	_	9	9	1	_

TABLE 1 (Continued)

	Sept.	Oct.	Dec.	Jan.	March	April	May	June	August
Ch. laciniosus Schütt	–	–	–	–	–	26	6	–	1
Ch. lorenzianus Grun.	–	–	–	–	–	1	–	–	–
Ch. pseudocrinitus Ostf.	–	–	–	–	–	–	–	–	1
Ch. radians Schütt	–	–	–	–	–	29	–	–	–
Ch. socialis Laud.	–	–	–	–	–	1	–	–	–
Ch. subsecundus (Grun.) Hust.	–	–	–	–	–	1	–	–	–
Ch. teres Cleve	–	–	–	–	–	6	–	–	1
Cocconeis Scutellum Ehr.	–	–	–	–	1	–	–	–	–
Corethron hystrix Hensen	–	–	1	1	–	3	–	–	1
Coscinodiscus spp.	2	–	1	–	–	–	1	–	1
C. centralis Ehr.	2	3	5	9	3	12	24	–	4
C. excentricus Ehr.	3	4	7	8	1	5	1	1	3
C. radiatus Ehr.	–	–	–	–	–	–	4	–	–
Cyclotella sp.	–	–	–	1	–	–	–	–	–
Detonula confervacea (Cleve) Gran	–	–	–	1	1	11	2	–	–
Eucampia zoodiacus Ehr.	–	–	–	–	–	6	–	–	–
Fragillaria sp.	–	–	–	–	–	1	–	–	–
Grammatophora marina (Lyngb.) Kütz.	1	–	1	–	–	–	–	–	–
Guinardia flaccida Prerag.	7	–	–	1	–	–	–	1	9
Leptocylindrus danicus Cleve	–	–	–	2	–	3	3	–	3
Lichmophora abbreviata Ag.	–	–	–	–	–	–	–	–	1
Melosira sp.	–	–	–	1	–	3	–	–	–
M. sulcata (Ehr.) Kütz.	3	3	3	3	4	1	7	2	1
Navicula sp.	2	2	1	–	–	–	–	–	–
N. distans W. Smith	–	1	–	2	1	3	7	1	4
N. Vanhoeffenii Cleve	–	–	–	–	2	–	–	–	–
Nitzschia Closterium W. Smith	–	–	–	2	1	11	2	–	6
N. delicatissima Cleve	–	–	–	–	–	–	–	1	–
N. longissima Cleve	–	–	–	6	–	–	–	2	–
N. seriata Cleve	–	–	–	1	2	–	–	–	–
Pinnularia sp.	1	–	–	–	–	–	–	1	–
Pleurosigma Normani Ralfs	1	–	1	4	4	4	4	1	4
Porosira glacialis (Grun.) Jörg.	–	–	–	–	4	46	12	–	–
Rhizosolenia spp.	–	1	–	–	2	–	–	3	–
Rh. alata Brightw.	1	–	–	–	6	5	–	–	7
Rh. Bergoni Perag.	–	–	–	–	–	2	–	–	–
Rh. calcar-avis Cleve	–	–	–	–	–	–	–	–	1
Rh. fragilissima Bergon.	–	–	–	–	–	2	–	–	–
Rh. hebatata var. *semispina* (Hensen) Gran	1	–	–	–	–	6	4	–	4
Rh. imbricata var. *Shrubsolei* (Cleve) Schroeder	–	–	–	–	1	38	8	–	3
Rh. setigera Brightw.	1	–	–	–	–	–	–	–	–
Rh. styliformis Brightw.	–	–	–	–	–	–	–	–	5
Sceletonema costatum (Grev.) Cleve	–	–	–	4	1	–	–	1	2
Thalassionema nitzschioides Grun.	7	–	3	8	4	21	3	2	–
Thalassiosira spp.	1	–	2	5	1	–	–	1	–
Th. bioculata (Grun.) Ostf.	1	–	–	–	2	–	–	–	–
Th. decipiens (Grun.) Jörg.	–	1	2	8	4	–	–	3	–
Th. gravida Cleve	–	–	–	–	1	2	–	–	–
Th. hyalina (Grun.) Gran	1	–	–	–	1	26	2	–	–
Th. Nordenskioeldii Cleve	6	2	1	3	9	59	16	4	2
Thalassiothrix longissima Cleve and Grun.	–	–	–	–	–	1	–	–	–
Triceratium alternans Bail.	–	–	–	1	–	–	–	–	–

TABLE 2

Dinophyceae	No. of Stations at which present								
	Sept.	Oct.	Dec.	Jan.	March	April	May	June	August
Amphidinium oceanicum Lohm.	1	–	–	–	–	–	–	–	–
Ceratium bucephalum (Cleve) Cleve	–	–	–	–	–	–	–	–	1
C. *Fusus* (Ehr.) Duj.	4	2	2	3	1	2	4	1	8
C. *lineatum* (Ehr.) Gran	4	3	2	4	–	–	–	–	2
C. *longipes* (Bail.) Gran	4	1	–	1	1	–	17	1	6
C. *macroceros* (Ehr.) Cleve	–	–	–	–	–	–	–	–	3
C. *tripos* (O.F.M.) Nitzsch.	2	3	2	4	2	3	2	–	8
C. *tripos* var. *atlanticum* Ostf.	–	–	–	–	–	–	–	–	9
C. *tripos* f. *subsalsum* Ostf.	–	–	–	–	–	–	–	–	4
Dinophysis spp.	–	–	1	–	–	–	–	–	2
D. *acuminata* Clap & Lach.	4	1	–	–	–	3	–	1	2
D. *norvegica* Clap & Lach.	–	–	–	–	–	–	–	–	1
D. *Ovum* Schütt	1	1	1	–	–	1	–	1	2
D. *robusta* Gran & Bra.	1	–	–	–	–	–	–	–	–
D. *sphaerica* Stein	–	1	–	–	–	–	–	–	–
Exuviaella spp.	2	6	4	1	–	–	–	–	–
E. *baltica* Lohm.	–	1	–	2	1	–	–	–	–
E. *marina* Cienkowski	5	1	–	6	1	–	–	1	–
Goniaulax spp.	–	2	1	–	–	4	1	–	–
G. *tamarensis* Lebour	1	1	1	–	–	–	1	–	2
Mesoporos perforata (Gran) Lillick	–	–	5	–	–	–	–	–	–
Noctiluca miliaris Sur.	–	–	1	–	–	–	6	–	4
Peridinium spp.	8	5	1	4	1	14	40	3	9
P. *americanum* Gran & Bra.	1	2	–	–	–	–	–	–	–
P. *breve* Paulsen	1	4	–	–	1	–	–	–	–
P. *conicoides* Paulsen	–	2	1	–	–	–	–	–	–
P. *conicum* (Gran) Ostf. & Schmidt	–	–	–	–	–	17	–	1	–
P. *conicum* var. *Asamushi*	1	1	1	–	–	–	–	–	–
P. *crassipes* Paulsen	–	–	–	–	–	–	–	–	4
P. *denticulatum* Gran & Bra.	1	2	–	–	1	–	–	–	–
P. *depressum* Bail.	1	–	1	–	1	9	12	1	3
P. *Granii* Ostf.	–	1	–	1	2	–	–	–	–
P. *minusculum* Pav.	–	1	–	1	–	–	–	–	–
P. *novascotiense* Gran & Bra.	–	1	–	–	–	–	–	1	–
P. *simplex* Gran & Bra.	2	3	–	2	2	–	–	1	–
P. *trochoideum* Smith	5	–	–	–	–	–	1	–	–
Phalocroma sp.	–	–	–	1	1	–	–	–	–
P. *parvulum* (Schütt) Jörg.	–	–	–	1	–	–	–	–	–
Prorocentrum micans Ehr.	4	3	3	3	–	–	–	–	1
P. *minimum* Schiller	–	–	1	–	–	–	–	–	–
P. *Scutellum* Schröder	–	–	–	–	–	1	1	1	1

TABLE 3

Coccolithophoridaceae, Silicoflagellata, etc.	No. of Stations at which present								
	Sept.	Oct.	Dec.	Jan.	March	April	May	June	August
Acanthoica acanthifera Lohm.	1	–	–	–	–	–	–	1	–
A. acanthos Schiller	9	3	4	8	6	–	–	1	–
A. coronata Lohm.	–	–	–	–	1	–	–	–	–
A. monospina Schiller	1	–	–	–	1	–	–	–	–
Calytrosphaera uvella Schiller	–	–	–	–	1	–	–	–	–
Coccolithus pelagicus (Wall.) Schiller	–	–	–	1	–	–	–	–	–
Discosphaera tubifer (Murr. & Blackman) Lohm.	–	–	–	–	1	–	–	–	–
Lohmanosphaera sp.	–	–	–	1	1	–	–	–	–
L. adriatica Schiller	–	–	–	–	1	–	–	–	–
Pontosphaera Bigelowi Gran & Bra.	1	–	–	–	–	–	–	–	–
P. Huxleyi Lohm.	5	2	–	3	1	–	–	1	2
P. ovalis Schiller	–	–	–	1	–	–	–	–	–
Rhabdosphaera stylifer Lohm.	–	1	–	1	1	–	–	–	–
R. tubulosa Schiller	–	–	–	1	–	–	–	–	–
Scyphosphaera Apsteini Lohm.	–	–	–	–	1	–	–	–	–
Syracosphaera sp.	6	–	–	–	1	–	–	–	–
S. mediterranea Lohm.	–	–	–	–	1	–	–	–	–
S. pulchra Lohm.	–	1	–	–	–	–	–	–	–
Dictyocha fibula Ehr.	1	1	–	1	1	–	–	1	–
D. fibula var. *messanensis* (Haek.) Lemm.	–	–	–	–	–	–	–	2	–
Distephanus speculum (Ehr.) Haek.	1	–	–	2	–	3	–	–	2
Ebria antiqua Schulz	–	–	1	–	–	–	–	–	–
E. tripartita (Schum.) Lemm.	–	–	–	–	–	1	–	–	–
Gloeocapsa sp.	1	–	–	1	–	–	–	–	–
Merismopedia sp.	–	–	–	1	–	–	–	–	–
Flagellates, Spores, etc.	9	6	5	9	4	1	–	5	–

TABLE 4.—September, 1933. Station 1742.

	Cells per Liter				
Species Depth	1 m.	10 m.	30 m.	50 m.	75 m.
Actinoptychus undulatus	--	--	55	--	--
Coscinodiscus centralis	--	--	55	--	--
Guinardia flaccida	--	--	55	--	--
Navicula distans?	--	55	--	--	55
Nitschia Closterium	--	--	--	55	--
Thalassionema nitzschioides	--	--	220	55	--
Thalassiosira Nordenskioeldii	--	220	165	330	--
Ceratium lineatum	--	--	275	55	--
C. longipes	--	--	55	--	--
Dinophysis acuminata	--	--	55	--	--
Peridinium trochoideum	--	--	275	--	--
P. simplex	--	--	165	--	--
Prorocentrum micans	--	--	55	--	--
Acanthoica acanthos	--	110	--	--	--
Pontosphaera Huxleyi	--	--	55	--	--
Flagellates	220	220	440	385	--
Protozoa	165	110	--	--	110

TABLE 5.—September, 1933. Station 1748.

	Cells per Liter				
Species Depth	1 m.	10 m.	30 m.	50 m.	80 m.
Thalassiosira sp.	110	--	--	--	--
Ceratium tripos	55	--	--	--	--
Peridinium trochoideum	500	385	--	110	110
Acanthoica acanthos	--	55	--	--	110
Spores, flagellates	1000	100	330	330	110
Protozoa	--	--	55	--	--

TABLE 6.—September, 1933. Station 1761

	Cells per Liter				
Species Depth	1 m.	10 m.	30 m.	50 m.	80 m.
Navicula sp.	--	--	220	--	--
Thalassionema nitzschioides	--	--	220	--	--
Thalassiosira sp.	55	--	--	--	--
Peridinium sp.	--	110	--	--	--
P. americanum	220	--	--	--	--
Syracosphaera	165	110	550	--	--
Gloeocapsa (Colony)	110	--	--	--	--
Flagellates	165	220	220	--	--
Protozoa	110	--	--	--	--

TABLE 7.—September, 1933. Station 1770.

	Cells per Liter				
Species Depth	1 m.	10 m.	30 m.	50 m.	80 m.
Coscinodiscus sp.	--	--	--	--	55
Guinardia flaccida	--	--	--	110	55
Nitzschia Closterium	--	--	55	--	--
Pinnularia sp.	--	55	--	--	--
Ceratium Fusus	--	110	--	--	--
Exuviaella marina	770	165	--	--	--
Peridinium sp.	4500	330	--	--	--
P. breve	--	--	--	--	55
Acanthoica acanthos	330	--	220	--	--
Pontoshpaera Huxleyi	--	--	55	--	--
Syrachosphaera	330	--	--	--	--
Phaeocystis sp.	--	--	220	--	--
Flagellates	440	440	820	--	550
Protozoa	660	55	--	55	55

Table 8.—September, 1933. Station 1789

		Cells per Liter		
Species	Depth 1 m.	10 m.	30 m.	45 m.
Coscinodiscus centralis	--	--	180	--
C. excentricus	65	--	--	--
Guinardia flaccida	200	--	23,300	12,000
Melosira sulcata	20	--	155	--
Navicula distans?	45	45	110	65
Pleurosigma Normani	65	110	90	45
Rhizosolenia setigera	--	--	110	--
Thalassionem nitzschioides	810	330	3,150	2.440
Thalassiosira bioculata	65	--	45	--
Th. Nordenskioeldii	--	285	1,000	90
Ceratium Fusus	45	--	20	20
C. lineatum	155	--	460	220
C. longipes	45	--	--	--
C. tripos	--	--	--	20
Dinophysis acuminata	20	20	--	65
D. Ovum	45	--	--	--
Goniaulax tamarensis	--	--	110	--
Peridinium sp.	155	--	--	90
P. depressum	--	175	90	65
Prorocentrum micans	110	90	310	350
Acanthoica acanthos	--	20	--	--
Pontosphaera Huxleyi	--	--	65	--
Dictyocha fibula	20	--	--	--
Flagellates	--	--	375	175
Protozoa	90	--	20	--

Table 9.—October, 1933. Station 1812.

		Cells per Liter	
Species	Depth 10 m.	30 m.	55 m.
Coscinodiscus centralis	20	65	--
C. excentricus	1585	660	495
Melosira sulcata	65	110	--
Navicula distans	20	20	20
Rhizosolenia sp.	--	--	45
Thalassiosira sp.	200	--	65
Ceratium Fusus	65	90	110
C. lineatum	200	20	45
C. tripos	--	--	20
Dinophysis acuminata	20	--	--
D. Ovum	45	65	110
Exuviaella marina	90	90	220
Goniaulax sp.	45	--	--
Peridinium sp.	20	--	--
P. breve	175	--	--
P. denticulatum	65	--	--
P. conicoides	--	--	65
P. conicum	--	90	--
P. simplex	--	20	--
Procentrum micans	2500	950	1600
Acanthoica acanthos	65	--	65
Flagellates	525	90	330
Protozoa	20	90	45

TABLE 10.—October, 1933. Station 1830

		Cells per Liter			
Species	Depth 1 m.	10 m.	30 m.	50 m.	80 m.
Actinoptychus undulatus	--	--	--	--	110
Melosira sulcata	--	--	175	640	1550
Navicula distans	--	--	45	20	130
N. Vanhoeffeni	--	--	--	--	155
Thalassiosira Nordenskioeldii	20	--	45	45	--
Ceratium tripos	--	--	20	--	--
Goniaulax sp.	--	--	--	20	--
Peridinium sp.	--	--	--	20	--
Pontosphaera Huxleyi	--	--	200	65	200
Rhabdosphaera styliformis	--	--	--	20	--
Syrachosphaera pulchra	--	--	--	90	--
Dictyocha fibula	--	--	--	20	--
Flagellates	--	--	175	65	45
Protozoa	--	--	45	200	375

TABLE 11.—October, 1933. Station 1855.

		Cells per Liter			
Species	Depth 1 m.	10 m.	30 m.	50 m.	80 m.
Coscinodiscus centralis	--	20	--	--	20
Melosira sulcata	--	20	--	--	--
Exuviaella sp.	220	--	--	--	--
Peridinium sp.	--	--	--	20	--
Flagellates	20	640	--	110	--
Protozoa	45	130	--	--	--

TABLE 12.—October, 1933. Station 1857.

		Cells per Liter		
Species	Depth 1 m.	10 m.	50 m.	80 m.
Coscinodiscus excentricus	20	20	--	45
Exuviaella sp.	45	20	155	110
Peridinium conicoides	--	--	20	--
Flagellates	200	45	2290	90
Protozoa	20	20	--	--

TABLE 13.—October, 1933. Station 1860.

		Cells per Liter			
Species	Depth 1 m.	10 m.	30 m.	50 m.	80 m.
Coscinodiscus centralis	45	--	--	45	--
C. excentricus	20	--	45	--	80
Ceratium Fusus	--	20	--	--	--
C. longipes	--	--	20	--	--
C. tripos	--	--	20	--	--
Exuviaella sp.	45	90	--	--	--
Peridinium sp.	--	--	--	20	--
Flagellates	--	--	--	20	--
Protozoa	--	90	--	90	20

TABLE 14.—December, 1933. Station 1864.

		Cells per Liter			
Species	Depth 1 m.	10 m.	30 m.	50 m.	80 m.
Coscinodiscus centralis	110	45	--	--	--
C. excentricus	--	20	--	45	20
Exuviaella sp.	--	--	20	--	--
E. minima	55	--	--	--	--
Ebria antiqua	55	--	--	--	--
Flagellates	--	45	20	--	20
Protozoa	--	20	--	20	--

TABLE 15.—December, 1933. Station 1871.

		Cells per Liter		
Species	Depth 1 m.	30 m.	50 m.	80 m.
Actinoptychus undulatus	110	--	--	--
Coscinodiscus centralis	--	65	--	20
C. excentricus	--	110	--	45
Melosira sulcata	--	--	--	155
Navicula distans?	--	20	--	--
Thalassiosira decipiens	--	65	--	20
Exuviaella sp.	--	20	--	20
Acanthoica acanthos	--	--	--	20
Flagellates	--	155	--	--
Protozoa	--	65	--	--

TABLE 16.—December, 1933. Station 1893.

		Cells per Liter		
Species	Depth 1 m.	10 m.	30 m.	80 m.
Coscinodiscus excentricus	--	200	--	--
Thalassionema nitzschioides	--	--	--	440
Thalassiosira sp.	--	--	--	220
Ceratium tripos	--	--	20	--
Exuviaella sp.	--	285	20	--
Acanthoica acanthos	20	20	--	220
Flagellates	--	65	--	110
Protozoa	65	155	110	--

TABLE 17.—December, 1933. Station 1899.

		Cells per Liter			
Species	Depth 1 m.	10 m.	30 m.	50 m.	80 m.
Coscinodiscus centralis	--	--	--	20	--
C. excentricus	--	--	45	--	--
Thalassionema nitzschioides	220	--	--	--	--
Thalassiosira sp.	110	--	--	--	--
Exuviaella sp.	--	--	--	45	--
Acanthoica acanthos	110	--	--	65	20
Coccolithus sp.	--	--	--	--	65
Flagellates	330	--	155	65	110
Protozoa	110	--	110	155	--

TABLE 18.—December, 1933. Station 1901.

	Cells per Liter	
Species Depth	1 m.	10 m.
Corethon hystrix	45	20
Coscinodiscus sp.	45	--
C. centralis	20	110
C. excentricus	200	65
Grammatophora marina	20	--
Melosira sulcata	90	90
Thalassionema nitzschioides	265	65
Ceratium Fusus	20	--
C. lineatum	45	20
C. tripos	45	20
Dinophysis acuminata	--	20
D. Ovum	20	--
Exuviaella sp.	20	110
Gymnidinium sp.	--	65
Noctiluca miliaris	45	--
Peridinium sp.	45	90
P. conicoides	--	65
Prorocentrum micans	375	375
Acanthoica acanthos	20	--
Flagellates	240	200
Protozoa	240	330

TABLE 19.—January, 1934. Station 1909.

	Cells per Liter				
Species Depth	1 m.	10 m.	30 m.	50 m.	80 m.
Coscinodiscus centralis	--	--	65	65	45
C. excentricus	65	175	265	240	110
Melosira sulcata	20	--	20	20	20
Nitzschia longissima	--	45	--	--	--
Thalassiosira decipiens	20	--	--	20	--
Ceratium tripos	--	--	--	20	--
Acanthoica acanthos	20	--	--	--	--
Pontosphaera Huxleyi	20	65	20	90	--
Rhabdosphaera tubulosa	--	--	40	--	--
Flagellates	65	65	110	220	--
Protozoa	20	--	--	--	--

TABLE 20.—January, 1934. Station 1913.

	Cells per Liter				
Species Depth	1 m.	10 m.	30 m.	50 m.	80 m.
Coscinodiscus centralis	--	--	--	65	90
C. excentricus	175	45	65	90	155
Melosira sulcata	330	155	--	175	220
Navicula sp.	--	45	90	20	20
Nitzschioides longissima	110	20	--	--	--
Pleurosigma Normani	--	--	65	45	45
Thalassionema nitzschioides	130	45	--	--	--
Thalassiosira decipiens	130	20	155	375	155
Ceratium Fusus	--	--	--	20	--
Exuviaella baltica	90	--	--	20	--
Flagellates	110	20	20	20	20
Protozoa	45	--	--	--	20

TABLE 21.—January, 1934. Station 1918.

	Cells per Liter				
Species Depth	1 m.	10 m.	30 m.	50 m.	80 m.
Coscinodiscus centralis	--	--	20	--	20
Leptocylindrus danicus	--	--	90	--	--
Nitzschia longissima	--	--	20	--	--
Sceletonema costatum	--	--	--	--	45
Thalassiosira decipiens	--	--	90	--	--
Ceratium Fusus	--	20	--	--	--
Exuviaella marina	--	20	--	--	--
Acanthoica acanthos	20	--	20	--	45
Flagellates	--	--	330	20	65
Protozoa	45	20	45	45	--

TABLE 22.—January, 1934. Station 1927.

	Cells per Liter			
Species Depth	1 m.	10 m.	30 m.	50 m.
Coscinodiscus centralis	--	20	45	--
Leptocylindrus danicus	--	--	90	--
Nitzschia longissima	--	--	45	20
Thalassionema nitzschioides	130	--	--	--
Thalassiosira decipiens	--	20	45	--
Th. Nordenskioeldii	--	--	--	90
Ceratium Fusus	--	--	20	--
C. lineatum	--	20	--	--
Exuviaella marina	45	--	--	--
Peridinium sp.	--	--	--	65
Flagellates	110	110	90	20
Protozoa	45	--	45	20

TABLE 23.—January, 1934. Station 1934.

	Cells per Liter		
Species Depth	1 m.	30 m.	50 m.
Actinoptychus undulatus	--	--	110
Coscinodiscus centralis	400	400	350
C. excentricus	200	350	220
Cyclotella sp.	20	--	--
Leptocylindrus danicus	155	--	--
Melosira sulcata	--	285	--
Nitzschia longissima	20	--	--
Pleurosigma Normani	20	45	--
Thalassionema nitzschioides	1475	1780	2795
Thalassiosira Nordenskioeldii	920	285	240
Triceratium alternans	45	--	--
Ceratium lineatum	65	--	20
C. tripos	--	20	45
Exuviaella marina	--	--	65
Prorocentrum micans	110	330	265
Acanthoica acanthos	20	--	--
Dictyocha fibula	20	--	--
Flagellates	155	20	--
Protozoa	45	45	45

TABLE 24.—March, 1934. Station 2022

Species	Depth 1 m.	Cells per Liter 10 m.	30 m.	50 m.	80 m.
Detonula confervacea	110	--	--	--	--
Rhizosolenia alata	275	385	--	--	--
Ceratium tripos	--	55	--	--	--

TABLE 25.—March, 1934. Station 2029.

Species	Depth 1 m.	Cells per Liter 10 m.	30 m.	45 m.
Chaetoceros sp.	--	--	880	--
Pleurosigma Normani	440	110	330	--
Porosira glacialis	6050	5107	7050	6600
Rhizosolenia alata	--	--	110	--
Thalassiosira hyalina	--	--	1210	--
Th. Nordenskioeldii	9250	6500	16250	33200
Peridinium sp.	110	--	--	--
P. americanum	220	--	--	--
Protozoa	--	550	220	220

TABLE 26.—March, 1934. Station 2042.

Species	Depth 10 m.	Cells per Liter 30 m.	50 m.	80 m.
Cocconeis Scutellum	--	--	110	--
Rhizosolenia alata	--	--	1210	--
Rh. Shrubsolei	--	--	220	--
Thalassionema nitzschioides	--	--	1320	--
Thalassiosira Nordenskioeldii	--	330	220	--
Ceratium Fusus	--	--	330	--
Exuviaella baltica	--	--	1100	660
Peridinium sp.	330	--	--	--
Syracosphaera sp.	--	--	110	165
Flagellates	--	--	1550	275
Protozoa	--	--	220	55

TABLE 27.—March, 1934. Station 2060.

Species	Depth 1-10 m.	Cells per Liter 30 m.	50 m.	80 m.
Nitzschia longissima	20	--	--	--
Thalassiosira Nordenskioeldii	45	--	90	--
Acanthoica acanthos	--	--	--	45
Syracosphaera sp.	65	--	--	--
Flagellates	65	--	--	--
Protozoa	130	--	--	--

Table 28.—March, 1934. Station 2069.

Species	Cells per Liter Depth 7 m.	27 m.
Actinoptychus undulatus	330	240
Coscinodiscus centralis	550	550
C. excentricus	1130	175
Navicula Vanhoeffeni	5000	3400
Nitzschia Closterium	--	45
Pleurosigma Normani	110	--
Porosira glacialis	460	410
Thalassionema nitzschioides	4160	990
Thalassiosira decipiens	--	850
Th. Nordenskioeldii	--	265
Ceratium longipes	--	20
Peridinium breve	--	90
P. denticulatum	20	--
P. depressum	20	--
Phalocroma sp.	65	--
Flagellates	20	--
Protozoa	110	65

TABLE 29.—April, 1934. Cells per column of water 1/10 M.2

Species Station	2080	2083	2086
Achnanthes taeniata	----	----	14,200,000
Chaetoceros diadema	286,350,000	----	58,500,000
Ch. atlanticus	----	----	3,366,000
Ch. constrictus	4,945,000	----	3,978,000
Ch. convolutus	115,000	1,260,000	104,000,000
Ch. debilis	9,200,000	----	4,750,000
Ch. decipiens	690,000	----	2,210,000
Ch. compressus	11,530,000	----	30,500,000
Ch. didymus	21,610,000	----	5,700,000
Ch. laciniosus	3,565,000	----	612,000
Ch. lorenzianus	3,450,000	----	----
Ch. radians	41,000,000	----	15,000,000
Ch. teres	560,000	----	----
Melosira sp.	----	----	790,000
Navicula distans	230,000	----	----
Porosira glacialis	----	----	65,600,000
Rhizosolenia semispina	----	----	29,000,000
Thalassiosira Nordenskioeldii	63,500,000	----	20,700,000

TABLE 30.—April, 1934. Cells per Column.

Species Station	2090	2098	2115
Achnanthes taeniata	32,300,000	572,500,000	3,220,000
Biddulphia aurita	655,000	----	----
Chaetoceros spp.	----	----	2,780,000
Ch. atlanticus	2,400,000	545,000,000	26,900,000
Ch. constrictus	437,000	----	----
Ch. convolutus	32,500,000	----	----
Ch. debilis	3,060,000	17,920,000	880,000
Ch. decipiens	11,800,000	----	----
Ch. diadema	2,400,000	620,000,000	33,500,000
Ch. didymus	13,550,000	----	----
Ch. laciniosus	5,900,000	----	4,980,000

Ch. radians	13,550,000	29,000,000	12,450,000
Corethran hystrix	----	1,380,000	----
Coscinodiscus centralis	----	----	146,000
Detonula confervacea	----	----	439,000
Leptocylindrus danicus	1,310,000	----	----
Navicula sp.	1,920,000	1,380,000	293,000
Nitzschia Closterium	218,200	----	732,000
Porosira glacialis	670,000,000	3,190,000,000	15,400,000
Rhizosolenia Shrubsolei	2,620,000	19,310,000	732,000
Thalassionema nitzschioides	4,370,000	----	2,050,000
Thalassiosira hyalina	31,500,000	567,000,000	11,300,000
Th. Nordenskioeldii	657,500,000	7,600,000,000	109,500,000
Thalassiothrix longissima	----	6,900,000	----
Peridinium spp.	----	1,380,000	293,000
P. conicum	437,000	----	----

TABLE 31.—May, 1934. Cells per Column.

Species Station	2168	2179	2121
Biddulphia aurita	234,000	----	----
Chaetoceros atlanticus	----	55,200	147,000
Ch. borealis	469,000	----	----
Ch. borealis var. *concavicornis*	3,280,000	----	----
Ch. convolutus	3,870,000	----	94,100
Ch. constrictus	703,000	----	----
Ch. decipiens	820,000	55,200	94,100
Ch. didymus	3,280,000	----	110,000
Ch. furcellatus	3,630,000	----	----
Coscinodiscus centralis	----	18,400	36,800
Rhizosolenia semispina	------	----	36,800
Rh. Shrubsolei	117,000	----	18,400
Thalassionema nitzschioides	234,000	----	----
Thalassiosira Nordenskioeldii	1,170,000	----	----
Ceratium Fusus	----	----	18,400
C. longipes	----	18,400	----
Peridinium spp.	234,000	147,000	405,000
P. depressum	----	91,000	----

TABLE 32.—May, 1934. Cells per Column.

Species Station	2186	2201	2205
Chaetoceros constrictus	11,140,000	----	----
Ch. convolutus	72,000	----	----
Ch. debilis	3,150,000	----	----
Ch. decipiens	270,000	----	----
Ch. didymus	558,000	----	----
Ch. laciniosus	72,000	----	----
Coscinodiscus centralis	18,000	----	11,100
Detonula confervacea	54,000	----	----
Melosira sulcata	216,000	----	----
Porosira glacialis	2,195,000	----	----
Rhizosolenia semispina	18,000	----	----
Thalassiosira Nordenskioeldii	18,000	----	----
Ceratium longipes	----	16,600	33,400
Noctiluca miliaris	----	----	11,100
Peridinium sp.	72,000	82,700	66,800
P. depressum	----	82,700	55,600

Table 33.—June, 1934. Station 2220.

Species		Cells per Liter	
	Depth 1 m.	40 m.	70 m.
Rhizosolenia sp.	--	45	--
Peridinium sp.	--	20	--
Acanthoica acanthifera	--	45	--
Flagellates	20	130	20
Protozoa	--	20	--

Table 34.—June, 1934. Station 2224.

Species		Cells per Liter		
	Depth 1 m.	30 m.	50 m.	80 m.
Melosira sulcata	--	--	200	--
Thalassiosira sp.	--	--	--	20
Rhizosolenia sp.	45	--	--	--
Ceratium longipes	20	--	--	--
Peridinium	--	20	20	--
Acanthoica acanthos	20	--	--	--
Flagellates	485	65	20	--
Protozoa	240	--	65	45

Table 35.—June, 1934. Station 2226.

Species		Cells per Liter		
	Depth 1 m.	10 m.	30 m.	50 m.
Chaetoceros decipiens	--	--	45	--
Ch. furcellatus	--	--	45	--
Guinardia flaccida	20	--	--	--
Melosira sulcata	45	--	420	--
Nitzschia longissima	65	--	45	--
Pinnularia sp.	--	--	45	--
Rhizosolenia sp.	45	--	--	--
Thalassionema nitzschioides	200	--	--	--
Thalassiosira sp.	20	--	420	--
Th. Nordenskioeldii	220	420	--	130
Dinophysis acuminata	65	--	--	--
D. Ovum	--	20	--	--
Peridinium sp.	45	--	20	20
P. conicum	--	400	--	--
P. depressum	20	--	--	--
P. Granii	--	640	--	--
P. Simplex	200	--	--	--
Flagellates	4840	9640	2070	90
Protozoa	1690	770	440	--

Table 36.—June, 1934. Station 2228.

Species		Cells per Liter	
	Depth 10 m.	30 m.	80 m.
Actinoptychus undulatus	--	45	--
Chaetoceros decipiens	20	110	--
Coscinodiscus excentricus	--	45	90
Melosira sulcata	--	300	--
Pleurosigma Normani	155	130	20
Thalassionema nitzschioides	--	45	--
Thalassiosira decipiens	375	155	--
Th. Nordenskioeldii	--	--	20
Flagellates	--	20	--

TABLE 37.—August, 1936.

Key: 4—dominant; 3—common; 2—rare; 1—very rare.

Species	Station 2659	2660	2663	1	3
Chaetoceros affinis	–	–	–	1	–
Ch. atlanticus	–	–	–	–	1
Ch. borealis	–	–	–	1	1
Ch. compressus	–	–	–	4	–
Ch. constrictus	–	3	–	2	–
Ch. convolutus	–	–	–	2	–
Ch. crinitus	–	–	–	1	–
Ch. decipiens	1	1	–	–	–
Ch. didymus	1	–	–	–	–
Ch. laciniosus	–	–	–	2	–
Ch. pseudocrinitus	–	–	–	3	–
Ch. teres	–	–	–	4	–
Corethron hystrix	–	–	–	1	–
Coscinodiscus centralis	–	–	–	–	2
C. excentricus	–	–	–	–	1
Guinardia flaccida	2	2	2	–	2
Leptocylindrus danicus	–	2	–	1	–
Lichmophora abbreviata	–	–	–	1	–
Navicula sp.	–	–	–	1	1
Nitzschia Closterium	–	1	–	2	4
Pleurosigma Normani	–	–	–	1	2
Rhizosolenia alata	4	4	1	–	–
Rh. calcar-avis	–	–	–	4	–
Rh. semispina	1	1	1	–	–
Rh. Shrubsolei	–	1	–	3	–
Rh. styliformis	–	–	–	4	4
Sceletonema costatum	–	–	–	–	–
Thalassiosira Nordenskioeldii	–	–	–	1	–
Ceratium bucephalum	1	–	–	–	–
C. Fusus	1	1	1	1	–
C. lineatum	1	1	–	–	–
C. longipes	2	1	–	–	–
C. macroceros	1	1	1	–	–
C. tripos	1	1	–	–	1
C. tripos var. *atlanticus*	3	1	2	1	–
C. tripos var. *subsalsum*	3	1	–	–	–
Dinophysis acuminata	1	1	–	–	–
D. norvegica	1	–	–	–	–
D. Ovum	–	1	–	–	–
Gymnodinium sp.	–	–	–	1	1
Noctiluca miliaris	1	–	–	–	1
Peridinium sp.	1	1	–	–	–
P. crassipes	2	2	–	–	–
P. depressum	–	–	–	1	1
Prorocentrum micans	1	–	–	–	–
P. Scutellum	–	–	–	1	–
Pontosphaera Huxleyi	–	–	–	1	–
Dictyocha fibula	–	2	–	–	–
Distephanus speculum	–	1	–	–	–

Contribution No. 198

NOTES AND DESCRIPTIONS OF NEW SPECIES OF CALLIOSTOMA, GAZA AND COLUMBARIUM (MOLLUSCA); OBTAINED BY THE HARVARD-HABANA EXPEDITION OFF THE COAST OF CUBA *

BY W. J. CLENCH AND C. G. AGUAYO

The following notes and descriptions of new species are based for the most part on collections of mollusks obtained by the *Atlantis* on her cruise in the West Indies during February-March, 1938. There is included also a description of a new *Calliostoma* collected by the *Hassler*, during her voyage along the South American coast in 1872.

In working up the *Atlantis* Calliostomas, it was found necessary to review critically all of the known Western Atlantic species. We append the following notes on this group in addition to the new species obtained.

Genus CALLIOSTOMA Swainson

Genotype *Trochus conulus* Linné

CALLIOSTOMA VELIEI Pilsbry

(PLATE 28, FIG. 2)

Calliostoma veliei Pils. 1900, Nautilus 13, p. 128 (Caxambas, Florida).

This species has been confused apparently with *C. jujubinum* Gmel. It is, however, a well marked form and can be differentiated from this latter species by its smaller size, being inperforate and by a series of red maculations on the periphery of each whorl. So far as we can determine, it has been known heretofore only from the type locality. We can add the following records:

Florida: Sanibel, Lee Co.; Off Sombrero Key.

Bahamas: Dick's Point, Nassau, New Providence; Campdown, 4 mi. E. of Arthurs Town, Cat Island.

---

* Contribution Nº 198 of the Woods Hole Oceanographic Institution.

CALLIOSTOMA JUCUNDUM (Gould)

Trochus jucundus Gould 1849, Proc. Boston Soc. Nat. Hist. 3, p. 91 (New Zealand); 1852, United States Exploring Expedition **12**, p. 177, pl. 12, fig. 209 a-b.
Calliostoma riöensis Dall 1889, Proc. United States Nat. Mus. **12**, p. 345, pl. 12, fig. 5. (Encuados Islets, Rio Janeiro [United States Exploring Expedition]; "Albatross" station 2762, off Rio Janeiro in 59 fathoms, and stations 2764 and 2765 off Rio la Plata in 10-12 fathoms.)

Through a curious error, Gould described his material as coming from "New Zealand", though a specimen of Gould's original lot in our possession is labeled "Rio Janeiro, Brazil". Dall has apparently redescribed the same material under the name of *riöensis*, as he credits a part of his original series to the United States Exploring Expedition. Later (Nautilus **10**, 1897, p. 123) he lists *jucundum* among a series of species submitted to him by Dr. H. V. Ihering that had been collected at Bahia, Brazil.

Suter does not mention *jucundum* in his comprehensive monograph on the New Zealand Mollusca (Manual of the New Zealand Mollusca, Wellington, 1913, pp. 144-148) nor is it included in a revision of the New Zealand species by Oliver (Proc. Mala. Soc. London **17**, pp. 107-115, 1926).

In the original citation by Dall (l. c. p. 345) he states... "This species recalls *C. jucundum* Gould, from New Zealand and *C. euglyptum* Adams, from Florida, but is sufficiently distinct from either. It is less elegantly painted than *C. jucundum*, and the same may be said of its relation to the finer specimens of *C. euglyptum*, which also has its whorls more rounded and its flammules more regular."

The difference noted by Dall between *riöensis* and *euglyptum* certainly hold true. However, the only difference noted between this new form and *jucundum* is that the former was "less elegantly painted", a character of considerable variation in this species.

The *Hassler* obtained a small series of *C. jucundum* off Cape Bermeja, Argentina (South Lat. 41° 17′) in 17 fathoms.

Calliostoma (Calliostoma) blakei, new. species

(PLATE 28, FIG. 6)

Description.—Shell small, umbilicated, rather solid, depressed and angulated. Whorls 5, angulated at the periphery. Color a grayish white faintly mottled with pale brown, the shell surface in somewhat shining. Aperture subcircular with the interior nacreous. Spire depressed. Lip simple. Umbilicus small but deep. Columella fairly broad, concavely arched and possessing a small pit or depression at its base. This depressed area is nacreous. Sculpture consisting of many minute spiral threads or lirae, none of which are beaded. Body whorl with a biangulated periphery. Base of body whorl rounded with the spiral lirae continuing to the umbilicus.

Greater diam.	*Lesser diam.*	*Height*	*Aperture*	
6.2	5.7	5.1	3 × 3.5 mm.	Holotype

Holotype.—Mus. Comp. Zoöl. no. 89661, *Hassler* Expedition, off Cape Bermeja, Argentine (South Lat. 41° 17′) in 17 fathoms. Paratypes in the Mus. Comp. Zoöl. and Mus. Poey in Havana.

Remarks.—This species superficially is very much like *C. coppingeri* Smith from the same area along the Argentine Coast. Under small magnification, however, the differences seen are great. The only close resemblance is that of the angulated periphery. *C. blakei* differs from *C. coppingeri* by being umbilicated and possessing much finer and *non* beaded sculpture. In addition, *coppingeri* lacks the columellar depression, has beaded chords, and, in live shells, has the outer surface noticeably nacreous.

This species has been named for Mr. J. H. Blake, the artist and conchologist of the *Hassler* voyage.

A large series of *C. coppingeri* was collected at this same station by the *Hassler*. The type locality of this species as given by Smith (Ann. Mag. Nat. Hist. (5), **6**, p. 320, 1880) is off the mouth of the Rio de la Plata (South Lat 30° 47′; West Long. 55° 17′.) Dall (Proc. United States Nat. Mus. **12**, p. 344, 1889) adds an additional record of ''off Cape Delgado'' which extends the range south about 700 miles. Cape Bermeja is within this area, approximately 100 miles north of Cape [Punta] Delgado.

Calliostoma (Calliostoma) schroederi, new. species

(PLATE 28, FIG. 3)

Description.—Shell trochoidal, imperforate, fairly solid and somewhat shining. Whorls 7½, regularly increasing in size. Aperture subquadrangular. Spire produced and slightly concave. Periphery sharply keeled and margined by a double row of heavily beaded chords with a much finer beaded chord between them. Below the suture and again above the upper peripheral chord there are single, finely beaded chords. Between these are 4 narrow spiral brownish bands slightly inset in grooves. Similar brownish bands are found between all of the beaded chords. These bands apear to be the only color indicated on the shell which, otherwise, is a grayish white. Base of body whorl flattened with 7 incised, narrow, brownish bands. Columella arched inwardly, flattened and margined on its outer edge with a low axial ridge with a faintly beaded chord encircling the slight umbilical depression. Axial sculpture of very fine growth lines.

Greater diam.	*Lesser diam.*	*Height*	*Aperture*	
25	22.1	25	11 × 9 mm.	Holotype
26	23	23 (broken)	12.2×11.3 „	Paratype

Holotype.—Mus. Comp. Zoöl. no. 135002. *Atlantis* station no. 2981 off northern Cuba (North Lat. 22° 48′; West Long 78° 48′) in 225 fathoms, March 10, 1938. Three paratypes from the same station in the Mus. Comp. Zoöl. and Mus. Poey, Habana. Also one paratype from station 2999-a, off Matanzas Bay in 145 fathoms.

Remarks.—All four specimens were collected dead and with the base injured by hermit crabs. In relationship, this species seems to be nearest to *C. indiana* Dall, but the present new form is nearly three times larger. (6½ whorls are given for *C. indiana*, the measurement of *C. schroederi* at this point is 15 mm., or about double the height of the former species). The development of the two very strong peripheral beaded chords, particularly on the body whorl, and the almost entire absence of sculpture on the base and above the peripheral chords, are quite different from *C. indiana.*

Dall proposed the Section *Eucasta* for *C. indiana,* placing sectional value on his species because of the presence of a ''moderate sulcus near the periphery'', the other characters being similar to *Calliostoma* s. s. No indication of this sulcus appears in *C. schroederi,* other than the area broken by hermit-crabs.

This species is named for W. C. Schroeder, in charge of the dredging operations during the trip of the *Atlantis.*

Calliostoma (Astele) bigelowi, new. species

(Plate 28, figs. 4-5)

Description.—Shell solid, depressed trochoid, keeled and widely umbilicated. Whorls 7¼ rapidly though regularly increasing in size. Ground color grayish white. Above the peripheral keel there are five narrow, brownish, spiral lines which upon reaching the body whorl divide, become parallel and are separated by a beaded chord. The keel is maculated with reddish, somewhat oblique, flames that are more or less regularly disposed. On the early whorls this keel appears as a slight inset with these reddish maculations showing. Base of body whorl with 8 spiral lines o fbrown, the one nearest to the umbilical area somewhat distant from the others. The remainder are closeset and superficially appear as a fairly broad band. Spire acute, somewhat reduced and decidedly concave. Umbilicus funnel shaped, very broad and deep, with the inner whorls seen as slightly offset. Lip simple. Margin of umbilicus sharp, almost formed at a right angle and not sculptured. Columella concavely arched and somewhat thickened. Aperture subquadrate and nacreous within. Sculpture above the periphery consisting of numerous, fine beaded chords appearing on the white inter-spaces between the brownish lines. Base of shell convex and smooth with only the numerous and fine growth striae showing.

Operculum horn colored, multispiral with 10 whorls, crossed with numerous and fine and somewhat sinuous lines of growth. This last is best seen in transmitted light.

Greater diam.	*Lesser diam.*	*Height*	*Aperture*	
33.5	29.5	25	15 × 13 mm.	Holotype

Holotype.—Mus. Comp. Zoöl. no. 135003, *Atlantis* station 2963-c, Bahia Cochinos, Cuba, in 205 fathoms, Feb. 25, 1938.

Remarks.—A single specimen only was collected. It appears to be very different from any so far known to us. In outline it is nearest to *C. benedicti* Dall from off Cape Lookout, North Carolina (200 fathoms). Our species differs, however, by being larger, more sharply keeled, having a more concave spire and especially in lacking all spiral sculpture on the base of the body whorl. Also the spiral sculpture above the periphery is much finer in *C. bigelowi.*

Named for Henry B. Bigelow, Director of the Woods Hole Oceanographic Instituttion, under whose direction the *Atlantis* Expedition was made.

Genus Gaza Watson

Gaza Watson 1879, Jour. Linn. Soc. 14, p. 601.

Genotype, *G. daedala* Watson

This genus consists of some of the most beautiful deep sea mollusks known. The entire shell is opalescent, most strikingly so on the umbilical pad or callous which is possessed by many of the species.

The following is a synopsis of the genus with records that are so far published.

Gaza daedala Watson

Gaza daedala Watson 1879, Jour. Linn. Soc. **14**, p. 602; Rept. Sci. Results *Challenger* Exp. **14**, p. 93, pl. 7, fig 12, 1886.

Type locality.—Challenger station 174, off Kandavu, Fiji Islands (South Lat. 19° 10′; East Long. 178° 10′) 610 fathoms in globigerina ooze.

Gaza fischeri Dall

Gaza fischeri Dall 1889, Bull. Mus. Comp. Zoöl. **18**, p. 355, pl. 37, fig. 6.

Type locality.—Blake station 221, off Santa Lucia, West Indies, 423 fathoms in gray ooze. Bottom temp 42° 75′ F.

The *Atlantis* obtained 4 specimens of this species at station 2291, off northern Santa Clara, Cuba (North Lat. 23° 21′; West Long. 80° 23′) in 475 fathoms, March 14, 1938. The two adult specimens measure 22 to 27 mm. ingreater diameter.

Gaza rathbuni Dall

Gaza rathbuni Dall 1889, Bull. Mus. Comp. Zoöl. **18**, p. 354 (foot note); 1889, Proc. United States Nat. Mus. **12**, p. 342, pl. 7, fig. 4.

Type locality.—Albatross station 2818, near the Galapagos Islands in 392 fathoms on a sand bottom. Bottom temp. 44°F.

Gaza superba (Dall)

Callogaza superba Dall 1881, Bull. Mus. Comp. Zoöl. **9**, p .49.
Gaza (*Callogaza*) *superba* Dall 1889, Bull. Mus. Comp. Zoöl. **18**, p. 354, pl. 22, figs. 4-4a.

Type locality.—Blake station 153 (1879-1880), off Montserrat, West Indies, 303 fathoms in lava sand. Bottom temp. 48.75°F.

Dall includes these additional records:

Blake	sta.	129,	off	Santa Cruz	in	314	fms.	ooze.	Temp.	48.5° F
„	„	274,	„	Barbados	„	209	„	sand & ooze.	„	53.5° „
„	„	275,	„	„	„	218	„	fine sand	„	52.5° „
„	„	281,	„	„	„	288	„	ooze.	„	46.5° „

Albatross (West Long. 88° 16′). Gulf of Mexico between the Mississippi delta and Cedar Keys, Florida, 324 fathoms in gray mud. Temp. 46.5°F.

Gaza watsoni (Dall)

Callogaza watsoni Dall 1881 Bull. Mus. Comp. Zoöl. **9**, p. 50.
Margarita filogyra Dall 1881, Bull. Mus. Comp. Zoöl **9**, p. 42 (young shell).
Gaza (*Callogaza*) *watsoni* Dall, 1889, Bull. Mus. Comp. Zoöl. **18**, p. 356, pl. 22, figs. 7-7a; pl. 23, figs. 1-1a; pl. 24, fis. 2-2a.

Type locality.—Blake station 12, off Havana, Cuba, in 177-200 fathoms.

A single specimen was obtained by the *Atlantis* off Matanzas, Cuba (North Lat. 23° 10′; West Long. 81° 29′) in 120 fathoms, March 17, 1938.

Dall's additional records are as follows:

Blake	sta	20,	off	Bahia Honda, Cuba,	in	220	fms.		Temp.	62°	F
"	"		"	Yucatan Strait	"	640	"		"		
"	"	273,	"	Barbados	"	103	"	Broken shell & coral	"	59.5°	"
"	"	282,	"	"	"	154	"	Sand	"	56°	"
"	"	296,	"	"	"	84	"	Hard bottom	"	61.5°	"

Dall instituted the genus *Callogaza* in 1881 for both *superba* and *watsoni* but did not name a genotype. In 1889 he reduced *Callogaza* to subgeneric rank, retaining *watsoni* as the single species. The figures 7-7a) of the adult shell on pl. 22 (1889) appear to be that of a true *Gaza*.

Dall described the genus *Microgaza* to include the species *rotella* (1881 Bull. Mus. Comp. Zoöl. **9**, p. 50) and later (1889) reduced *Microgaza* to a subgenus under *Gaza*. Thiele (1929, Hand Syst. Weichtierkunde **1**, p. 48) synonomizes *Microgaza* under *Solariella*. The figures of *rotella* as given by Dall (1889) pl. 22, fig. 5 and 5a certainly appear to be a depressed form of *Solariella*. The sculpture and shape of this species are not at all like any known *Gaza*.

In bathymetric distribution. *Gaza* has been found living between 84 and 640 fathoms, with bottom temperature differences of 42° to 62°F. The genus seems to favor a soft bottom, the two records of "hard bottom" and "broken shell and coral" may, of course, not have been the exact ecological areas from which the specimens were obtained, but only the general conditions of the entire drag. Small specific areas in any one haul may well include portions of soft bottom.

Records on the Pacific Ocean extend from the equator (off the Galapagos) to 19° 10′ south latitude (Fiji Islands) and in the

Atlantic from 13° (off the Barbados) to 29° north latitude (Gulf of Mexico).

Dall noted (l. c. p. 342) that the intestinal tract of *G. rathbuni* contained foraminifera.

COLUMBARIUM v. Martens

Pleurotoma (Columbarium) spinicincta v. Mts. 1881, Conchologische Mittheilugen **2**, p. 105.

Genotype, *Pleurotoma (Columbarium) spinicincta* v. Mts.

This genus was recently made the type of a new family, Columbariidae, by Tomlin (Ann. South African Museum **25**, p. 330, 1928). As far as we have been ab elto ascertain, our present new forms, described below, are the first record of the genus definitely occurring in the Atlantic Ocean, though two species, *C. formosissimum* Tom. and *natalense* Tom. occur off the coast of South Africa.

Columbarium atlantis, new. species

(PLATE 28, FIG. 1)

Description.—Shell rather thin, faintly shining, elongated and spinose. Color white. Whorls 9, regularly increasing in size. Nuclear whorls (1¼) bulbous, smooth and glass-like, remaining whorls sculptured. Aperture semicircular, the lower portion continued into a greatly lengthened and narrowly opened canal. Spire extended. Palatal lip thin. Sculpture of numerous peripheral spines developed along a somewhat sharpened carina. The spines are large and deflected downwards and are eight in number on the body whorl. Spiral sculpture of rather coarse thread-like ridges which are slightly wavy above the periphery of each whorl. The ridges are more strongly developed below the periphery on the body whorl, and continue spirally below for nearly half the length of the canal. Beyond this point the canal becomes smooth. Axial sculpture of fine and numerous growth lines.

Length	*Width (exclusive of spines)*	*Length of canal*	
35.2	6	20	mm. Holotype

Holotype.—Mus. Comp. Zoöl. no. 135004, *Atlantis* station no 2999, North Lat. 23° 10′; West Long. 81° 29′, off Matanzas, Cuba in 421 fathoms.

Paratypes.—*Atlantis* station no. 2988, N. Lat. 23° 15′, W. Long. 79° 57′, 1 specimen. Station no. 2989, N. Lat. 23° 10′, W. Long. 80° 04′, 1 specimen.

Remarks.—Only a single live specimen of this species was collected by the *Atlantis* party which appears to be the first record of this genus from the Atlantic.

C. atlantis differs from all other species in this genus by being smaller and having proportionately much longer and downwardly deflected spines. Though somewhat suggestive of *Ancistosyrinx* (Turridae) the bulbous nuclear whorls and lack of a sinus places the species in *Columbarium.* The persistance of the sculpture for nearly halfway along the canal is apparently common to all known species. On the present specimen there is a remnant of some light yellowish periostracum which is finely and erectly spinose on the fine ridges on the canal.

In relationship, *C. atlantis* seems to be nearest to *C. formosissimum* Tomlin from South Africa (between Cape Seal and Port Alfred). Ann. So. African Museum **25**, p. 331, pl. 25, fig. 1, 1928.

Columbarium bermudezi, new sp.

(PLATE 28, FIG. 7)

Description.—Shell imperforate, thin, elongated and keeled. Color a dull white or grayish white. Whorls 8, each with a peripheral keel strongly developed except on the two smooth nuclear whorls. Aperture subquadrate with the base continued with a greatly lengthened canal. Spire elevated. Palatal lip thin and simple. There is a peripheral keel which is first initiated on the second whorl as a series of small tubercles or elevations along the periphery. Between the fourth and fifth whorls these tubercles are connected by a keel and beyong this point the keel becomes very strong and the tubercles much less so. On the last two whorls the tubercles form a series of rather evenly spaced crenulations. Sculpture of exceedingly fine growth lines. No spiral sculpture indicated other than a few faint spiral threads on the canal. Canal long, about as long as the shell from the base of the aperture to the spire tip. Operculum not present.

Length	*Width (including keel)*	*Length of Canal*	
27.5 mm.	7 mm.	14 mm.	Holotype
25.5 „	7 „	11.7 „	Paratype
25 „	7 „	10 „	„

Holotype.—Mus. Comp. Zoöl. no. 135007, *Atlantis* station no. 2989, North Lat. 23° 10′; West Long. 80° 04′, off Sagua la Grande, Santa Clara, Cuba, in 360 fathoms. March 14, 1938.

One paratype from *Atlantis* station, no. 2988, North Lat. 23° 15′; West Long. 79° 57′, off Sagua la Grande, Santa Clara, Cuba, in 380 fathoms. March 14, 1938 (Deposited in the Museo Poey, Universidad de la Habana).

One paratype from same station 2988. (Deposited in Mus. Comp. Zoöl.).

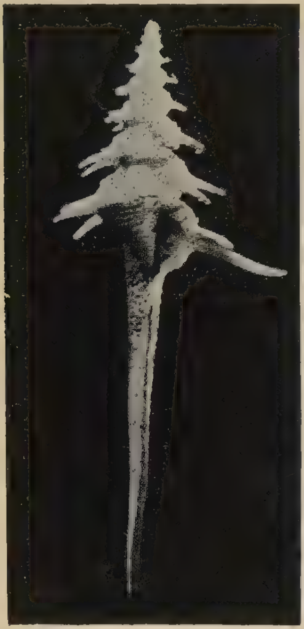
Remarks.—This new form occurred at the two localities given above which are only 10½ miles apart.

In general appearance, the species seems to be nearest to *C. formosissimum* Tomlin from Cape Natal, South Africa. From this species, *C. bermudezi* differs by being much smaller, and lacking entirely the two small keels below the peripheral keel.

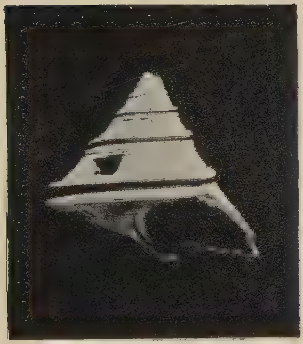
Named for Pedro J. Bermúdez, who is studying the foraminifera collected by the Atlantis.

EXPLANATION OF PLATE 28

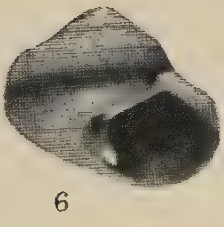
Fig. 1. *Columbarium atlantis* Cl. and Ag. Holotype, 2 ×
„ 2. *Calliostoma veliei* Pilsbry (Nassau, Bahamas). 4 ×
„ 3. *Calliostoma schroederi* Cl. and Ag. Hooltype, nat. size.
„ 4. *Calliostoma bigelowi* Cl. an dAg. Holotype, nat. size.
„ 5. *Calliostoma bigelowi* Cl. and Ag. Holotype, nat. size.
„ 6. *Calliostoma blakei* Cl. and Ag. Holotype, 4 ×
„ 7. *Columbarium bermudezi* Cl. and Ag. Paratype 2 ×



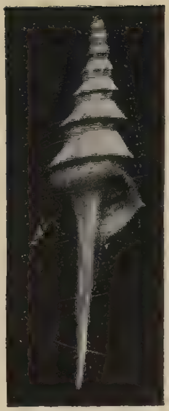
1



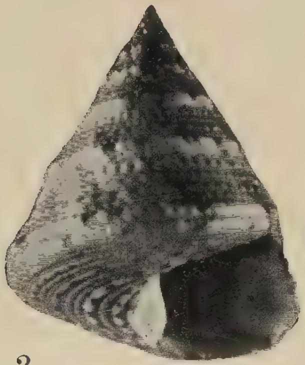
3



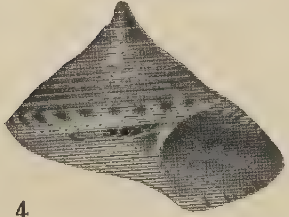
6



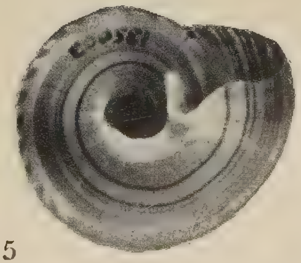
7



2



4



5

CLENCH y AGUAYO: *Calliostoma* and *Columbarium*.

Contribution No. 200

RESULTADOS DE LA PRIMERA EXPEDICION EN LAS ANTILLAS DEL KETCH ATLANTIS BAJO LOS AUSPICIOS DE LAS UNIVERSIDADES DE HARVARD Y HABANA

Aguayoina asterostomata, un foraminífero nuevo del Mar Caribe

POR PEDRO J. BERMÚDEZ
Museo Poey, Universidad de la Habana.

La primera expedición a bordo del *Atlantis* en los mares antillanos fué muy fructífera; el material de Foraminíferos colectado es tan rico y abundante que su estudio necesitará mucho tiempo, debido a la gran cantidad de especies que se están separando días tras día. De las ciento ocho estaciones hechas, cuarenta y dos suministraron muestras de los fondos.

El estudio de los Foraminíferos está siendo elaborado por el autor de estas líneas. Para adelantar se publicarán las especies nuevas en trabajos pequeños que saldrán según lo permitan los recursos económicos. Más tarde, usando todos los datos qeu aporte el estudio de este inmenso caudal de especies, se dará a la publicidad un estudio que las comprenda a todas, tratando de interpretar su vida histórica y ecología.

Con el presente trabajo se da a conocer un género y especie nueva para la Ciencia, de una forma arenácea de aspecto primitivo, que vive fuertemente adherida a las delicadas conchas del Molusco conocido científicamente como *Xenophora longleyi* Bartsch.

En este primer trabajo deseo hacer constar mi más sincero reconocimiento a todos aquellos que generosamente han colaborado en la empresa de esta fructífera expedición, llevada a cabo en los mares que circundan a Cuba. Especialmente al Señor Rector de la Universidad de la Habana, Ing. José M. Cadenas, por el interés y simpatía

Contribution No. 200 of the
Woods Hole Oceanographic Institution

que ha mostrado en todos los momentos ayudando en la organización de la expedición. Al Dr. Thomas Barbour, Director del Museo de Zoología Comparada de la Universidad de Harvard, que con su constante esfuerzo po rel desarrollo de las Ciencias Naturales en Cuba ha resultado ser un mentor auténtico de la juventud intelectual cubana. Y muy especialmente a mis distinguidos compañeros y amigos los Dres. Luis Howell Rivero y Carlos G. Aguayo, que son responsables del estudio de una buena parte de las maravillas arrancadas del seno de los mares.

Familia SACCAMMINIDAE

Sub-familia WEBBINELLINAE

Género **Aguayoina** Bermúdez, n. gen.

Genotipo *Aguayoina asterostomata* Bermúdez, n. sp.

Concha discoidal, arenácea, muy adherente, ligeramente convexa, con gran cantidad de sustancia quitinosa a la que fija conchas de Foraminíferos, espículas de esponjas y fragmentos de arena calcárea, con terminado finamente granuloso; abertura radiada, con múltiples hendiduras profundas que convergen en un punto central; color blanco grisáceo, a menudo manchada de anaranjado por descomposición del protoplasma celular.

El género ha sido nombrado en honor del Dr. Carlos G. Aguayo, Profesor de Zoología de la Universidad de la Habana, Cuba.

Aguayoina asterostomata Bermúdez, n. sp.

Los caracteres dados para definir este género son suficientes para describir esta interesante especie monotípica, que hace vida de comensal sobre las conchas del molusco *Xenophora longleyi* Bartsch. En adición deseo decir que he examinado una colonia compuesta de más de cien individuos, los más pequeños miden 2 mm. y los mayores miden 10 mm., habiendo muchos comprendidos entre ambas medidas. Algunas veces se encuentran tan próximos entre sí, que el material arenáceo de la periferia de los ejemplares junta uno al otro, mostrando una tendencia a formar colonias entre ambos, he examinado una cadena formada de diez y ocho ejemplares adultos fusionados, casi siempre encontrados en la parte más lisa de la cara ventral de las conchas de *Xenophora*, es muy raro encontrarlas sobre la cara dorsal, o en las partes más rugosas de los referidos caracoles.

Como he apuntado en la descripción del género, es arenácea, pero parece que en su origen o en la más tierna edad es quitinesa, y luego va pegando los granitos de arena, espículas de esponjas silíceas y gran cantidad de foraminíferos pequeños para dar consistencia a la pared. Muchos ejemplares muestran arrugas fuertes y cuarteaduras debido a la poca consistencia de las conchas al secarse.

El carácter más notable de esta curiosa forma es la abertura estrellada, formada casi siempre de diez y siete hendiduras profundas, con un tabique, aparentemente quitinoso en el centro de cada división, paralelo a la hendidura.

Este notable foraminífero presenta pocos caracteres para relacionarlo con algún género conocido. Los géneros *Iridia*(1) y *Diffusilina*(2) ambos de Heron-Allen & Earland, así como *Tholosina* Rhumbler(3) colocados en la familia *Saccamminidae* y en la sub-familia *Webbinellinae* parecen ser los más próximos a nuestra *Aguayoina*. La abertura de *Iridia* está colocada en los extremos de los tubos radiales de que carece nuestra nueva especie. En *Diffusilina* se observa la abertura en número considerable sobre pústulas colocadas irregularmente. La abertura de *Tholosina* es pequeña, circular y protuberante, colocada en la base de la concha.

Su presencia fué inadvertida por algún tiempo, distraído con el enorme aporte de material nuevo conseguido en la expedición; hubiera sido muy ventajoso haber estudiado los ejemplares vivos o al menos frescos, durante se efectuaba la colecta a bordo. El tiempo transcurrido desde la recolección ha modificado la forma fundamental de la especie, haciéndole arrugas fuertes y cuarteaduras al secarse.

Localidad: Genoholotipo Colección Cushman, Sharon, Mass. Atlantis Sta. 2963B, Bahía de Cochinos, Costa Sur de Cuba, 150 brazas de profundidad (Lat. 22° 12′ N. Long. 81° 10′ W.) Febrero 25, 1938.

El fondo sobre el cual vive la citada especie es el conocido en Oceanografía como *Limo de Globigerinas*, con un porcentaje grande de productos de desintegración coralina, siendo muy rico en especies pelágicas, y a causa de su relativa poca profundidad y cercanías a la costa contiene una rica y variada fauna de Foraminíferos muy ornamentados.

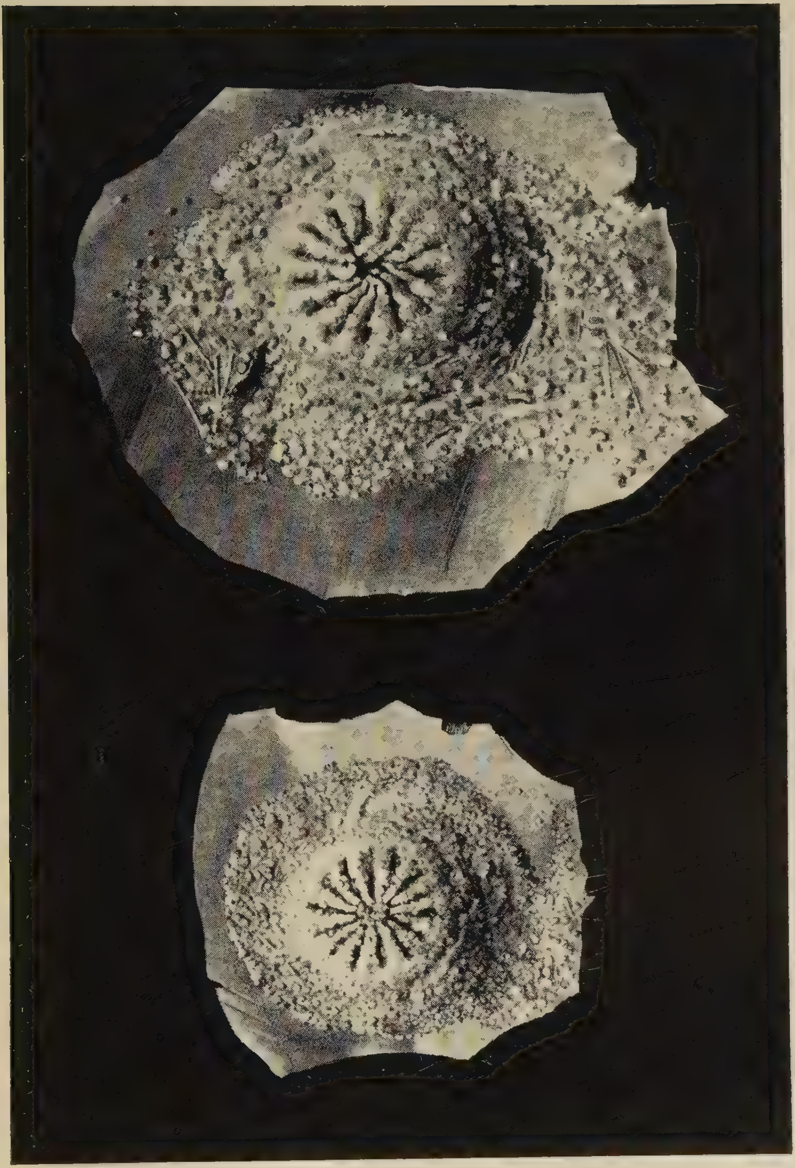
---

(1) *Iridia diaphana* Heron-Allen & Earland, 1914, Trans. Zool. Soc. London, vol. 20, pt. 12, p. 371, pl. 36, figs. 1-12.

(2) *Diffusilina humilis* Heron-Allen & Earland, 1924, Journ. Linn. Soc. Zool., vol. 35, p. 614, pl. 35, figs. 13-16.

(3) *Tholosina bulla* (H. B. Brady), Rhumbler, 1895, Nachr. Köngl. Ges. Wiss. Göttingen, p. 85.

Cotipos se han situado en los Museos de Zoología Comparada de Harvard, y Poey de la Universidad de la Habana, y en las colecciones privadas de Mrs. Dorothy K. Palmer, Habana; Mrs. Helen J. Plummer Austin, Texas; Dr. Arthur Earland, Inglaterra; Dr. Walter J. Parr, Victoria, Australia, y en la colección del autor.



Aguayoina asterostomata Bermúdez n. sp.

Fig. 1. Genoholotipo × 20 – Fig. 2. Cotipo × 10

Atlantis Sta. 2963B, Bahía de Cochinos, Costa Sur de Cuba, 150 brazas de profundidad. (Lat. 22° 12′ N. Long. 81° 10′ W.)

Report for the year 1937

THE
WOODS HOLE OCEANOGRAPHIC INSTITUTION

REPORT FOR THE YEAR
1937

TABLE OF CONTENTS

Page

I Trustees, as of December 31, 1937 3

II Members of the Corporation, as of December 31, 1937 ... 4

III Report of the Treasurer 5

IV Report of the Director 9

V Staff, as of December 31, 1937 18

APPENDIX: Reports of progress by investigators working at the Institution during 1937 19

I. TRUSTEES

(As of December 31, 1937)

To serve until 1941

THE COMMANDANT (Admiral R. R. Waesche), U. S. Coast Guard, for the time being, Washington, D.C.
MARION EPPLEY, Newport, R.I.
THE HYDROGRAPHER (Capt. L. R. Leahy), U. S. Navy Department, for the time being, Washington, D.C.
T. H. MORGAN, California Institute of Technology, Pasadena, Calif.
THE DIRECTOR, U. S. Coast & Geodetic Survey, for the time being, Washington, D.C.
B. W. ST. CLAIR, Cambridge, Mass.

To serve until 1940

WILLIAM BOWIE, U. S. Coast & Geodetic Survey, Washington, D.C.
A. G. HUNTSMAN, University of Toronto, Toronto, Canada.
COLUMBUS O'D. ISELIN, Woods Hole Oceanographic Institution, Woods Hole, Mass.
ALFRED C. REDFIELD, Harvard University, Cambridge, Mass.
HENRY L. SHATTUCK, Boston, Mass.
T. WAYLAND VAUGHAN, Washington, D.C.

To serve until 1939

ISAIAH BOWMAN, Johns Hopkins University, Baltimore, Md.
E. G. CONKLIN, Princeton University, Princeton, N.J.
ALEXANDER FORBES, Harvard Medical School, Boston, Mass.
ROSS G. HARRISON, Yale University, New Haven, Conn.
FRANK R. LILLIE, University of Chicago, Chicago, Ill.
HARLOW SHAPLEY, Harvard University, Cambridge, Mass.

To serve until 1938

CHARLES FRANCIS ADAMS, Boston, Mass.
THOMAS BARBOUR, Museum of Comparative Zoölogy, Cambridge, Mass.
BENJAMIN M. DUGGAR, University of Wisconsin, Madison, Wis.
JOHN A. FLEMING, Carnegie Institution, Washington, D.C.
FRANK B. JEWETT, New York, N.Y.
ELIHU ROOT, JR., New York, N.Y.

Ex officio

HENRY B. BIGELOW, Museum of Comparative Zoölogy, Cambridge, Mass.
LAWRASON RIGGS, JR., New York, N.Y.

OFFICERS

FRANK R. LILLIE, President of the Corporation, University of Chicago, Chicago, Ill.
LAWRASON RIGGS, JR., Treasurer, 120 Broadway, New York, N.Y.
HENRY B. BIGELOW, Clerk of the Corporation, Woods Hole, Mass.

II. MEMBERS OF THE CORPORATION

(As of December 31, 1937)

Charles Francis Adams, Boston, Mass.
Thomas Barbour, Museum of Comparative Zoölogy, Cambridge, Mass.
Henry B. Bigelow, Museum of Comparative Zoölogy, Cambridge, Mass.
Isaiah Bowman, Johns Hopkins University, Baltimore, Md.
The Commandant (Admiral R. R. Waesche), U. S. Coast Guard, for the time being, Washington, D.C.
E. G. Conklin, Princeton University, Princeton, N.J.
Benjamin M. Duggar, University of Wisconsin, Madison, Wis.
Marion Eppley, Newport, R.I.
John A. Fleming, Carnegie Institution, Washington, D.C.
Ross G. Harrison, Yale University, New Haven, Conn.
A. G. Huntsman, University of Toronto, Toronto, Canada.
The Hydrographer (Capt. L. R. Leahy), U. S. Navy Department, for the time being, Washington, D.C.
Columbus O'D. Iselin, Woods Hole Oceanographic Institution, Woods Hole, Mass.
Frank B. Jewett, New York, N.Y.
Frank R. Lillie, University of Chicago, Chicago, Illinois.
T. H. Morgan, California Institute of Technology, Pasadena, Calif.
The Director, U. S. Coast & Geodetic Survey, for the time being, Washington, D.C.
Alfred C. Redfield, Harvard University, Cambridge, Mass.
Lawrason Riggs, Jr., New York, N.Y.
Elihu Root, Jr., New York, N.Y.
B. W. St. Clair, Cambridge, Mass.
Harlow Shapley, Harvard University, Cambridge, Mass.
Henry L. Shattuck, Boston, Mass.
T. Wayland Vaughan, Washington, D.C.

III. REPORT OF THE TREASURER

To the Members and Trustees of the
Woods Hole Oceanographic Institution:
Gentlemen:

The accounts for the year 1937 have been audited by Messrs. Stagg, Mather & Hough, public accountants.

During the year bonds and preferred stock costing $138,271.91 were redeemed at a profit of $5,403.09 to which must be added $947.21 the reserve for amortization of premiums applicable to the securities sold. There was invested $159,107.94 from endowment cash in securities. $5,462.50 received as dividends in arrears at time of purchase of preferred stocks was applied to reduce their cost. Extra and special dividends on common stocks amounting to $10,071. were added to the Special Income Account.

The total gross income received during the year was .04973 of the cost of securities held at the end of the year and .05439 of the market at that time.

Fifteen hundred dollars received from the Bingham Oceanographic Foundation of Yale University, was applied in reduction of Operation of *Atlantis*.

Following are summaries of the various accounts:

BALANCE SHEET AS OF

ENDOWMENT FUND ASSETS

Investments, at cost:		
Endowment Fund bonds	$1,490,105.45	
(Quoted market value $1,404,391.87)		
Endowment Fund stocks	942,828.24	
(Quoted market value $820,186.87)		
Reserve Fund bonds	3,970.00	
(Quoted market value $3,200.00)		
Reserve Fund stocks	25,723.99	
(Quoted market value $13,963.97)		
		$2,462,627.68
Cash: In Banks		
Endowment Fund	$ 4,507.22	
Reserve Fund	3,125.30	7,632.52
		$2,470,260.20

PLANT ASSETS

Laboratory plant:		
Land	$ 27,072.32	
Buildings	323,213.12	
Laboratory equipment	21,361.93	
Crew room equipment	557.95	
Library	10,100.00	$382,305.32
Ship "Atlantis"		
Construction	$218,674.47	
Equipment	27,298.50	245,972.97
Small boat and equipment		6,570.55
Depreciation Fund (for periodical replacements)		
Investments—Bonds	$ 22,000.00	
(Quoted market value $22,036.56)		
Cash	6,307.52	28,307.52
		$663,156.36

CURRENT ASSETS

Current funds—Cash		$12,370.17
Special Income Account:		
Investments	$12,375.00	
Bonds (quoted market value $12,225).		
Stocks (quoted market value $1,553)	1,643.50	
Cash	4,773.83	
		18,792.33
Interest receivable (accrued interest included in cost of bonds purchased)		72.00
		$31,234.50

DECEMBER 31, 1937

ENDOWMENT FUNDS

Endowment Fund—General		$2,000,000.00	
Endowment Fund for upkeep of plant		419,419.96	
		$2,419,419.96	
Add:			
Realized net gain on securities called or sold	$10,846.49		
Reserve for amortization of bond premiums	7,174.46	18,020.95	
			$2,437,440.91
Reserve Fund			32,819.29
			$2,470,260.20

PLANT FUNDS

Plant Fund—General	$607,642.13
Plant Fund from current account	27,206.71
Reserve for deprecation (Reserve for periodic replacements)	28,307.52
	$663,156.36

CURRENT LIABILITIES AND SURPLUS

Accounts payable			$ 1,642.24
Current surplus and reserve for "working balance":			
Reserve for working balance		$ 5,000.00	
Current surplus:			
Balance at December 31, 1936, adjusted	$12,353.01		
Excess of income over expenditures for the year ended December 31, 1937	12,239.25	24,592.26	
			29,592.26
			$31,234.50

GENERAL ACCOUNT

Income:			
Income from Endowment Funds:			
Interest	$ 64,696.11		
Dividends (including special income of $10,071.00)	56,317.01		
	$121,013.12		
Less:			
Custodian fees and expenses	$ 1,468.73		$119,544.39
Expenses:			
Upkeep of Plant:			
Upkeep of buildings and grounds	$ 8,116.00		
Upkeep of *Atlantis*	12,978.78		
Upkeep of *Asterias*	52.62		
Insurance	5,816.74		
Depreciation	4,800.00		
		$ 31,764.14	
Operating expenses			
Operation of *Atlantis*	$ 28,901.55		
Operation of *Asterias*	900.58		
Scientists' salaries	27,200.14		
Scientific supplies and equipment	4,516.44		
Travelling expenses	424.56		
Publications	2,327.72		
Administration	7,098.19		
Amortization of bond premiums	1,800.63		
Contribution to retirement fund	1,771.19	$ 74,941.00	
		$106,705.14	
Expenditures for permanent plant additions:			
Additions to library		600.00	$107,305.14
Excess of income over expenditures			$ 12,239.25

RETIREMENT FUND

There was in the Retirement Fund at the end of the year the sum of $12,164.28 represented by credits on the Savings Bank books held by the Institution for the participants numbering seventeen.

Respectfully submitted,
LAWRASON RIGGS, JR.
Treasurer

April 22, 1938

IV. EIGHTH ANNUAL REPORT OF THE DIRECTOR FOR THE YEAR 1937

BY HENRY B. BIGELOW

Equipment

A temporary dark room was constructed on the third floor of the laboratory building to provide for special investigations, and additional lockers installed in the crew's club room.

On "Atlantis," considerable improvements were effected, including rearrangement of the plumbing system to obviate difficulties experienced in the past, and installation of additional blowers in the engine room, to provide more efficient ventilation in hot weather. In October a complete survey of the engine was made under the direction of the underwriters, after which the ship was declared in excellent condition. Minor improvements, in addition to routine replacements of equipment, include strengthening the trawling boom and the track on the mainmast.

The most important items of new scientific equipment are a rotary tank, 2 meters in diameter, built under Professor Rossby's supervision for the experimental study of circulatory systems in a rotating field, and a bottom sampler, of the new type developed in Dr. Hjort's laboratory, in Oslo. Four additional Nansen-type water bottles were also purchased, and an electric current meter is in course of construction, designed by Dr. Watson.

Library

The contribution to the library of the Marine Biological Laboratory was $600.

Purchases included 8 books and 1 complete and 1 partly completed back set; 40 current journal subscriptions were continued; 100 volumes were bound.

About 425 titles were received by gift or by exchange.

Personnel

The laboratory staff was enlarged by the promotion of Mr. Alfred Woodcock to the position of oceanographic technician, and by the appointment of two full-time technicians, one in chemistry and one in biology. Dr. C. E. Renn was appointed instructor in Sanitary Engineering, and Mr. C. O'D. Iselin assistant professor of Oceanography, at Harvard University, jointly with their membership on our staff.

Mr. C. O'D. Iselin was appointed Acting Director, for the summer, during the absence of the Director.

The following holders of Fellowships worked at Woods Hole during the summer: Coit M. Coker, Victor M. Emmel, Margaret Hotchkiss, W. H. Johnson, Bostwick H. Ketchum, Lois C. Lillick, Rudolph F. Nunnemacher, Frances L. Parker, Fred B. Phleger, Jr., W. R. Sawyer, Robert C. Stauffer, Th. von Brand and Talbot H. Waterman.

The list of visiting investigators for the year includes Dr. A. Abramowitz, Dr. Maurice Ewing, H. B. Hachey, Yvette Hardman, Christopher Hartley, Dr. Frederick L. Hisaw, Dr. James B. Lackey, Dr. Benjamin B. Leavitt, Raymond B. Montgomery, Dr. G. H. Parker, J. E. G. Raymont, Dr. Louis A. Toth and Dr. Unto Vartiovaara.

Thirteen assistants have worked for various members of the staff.

The following institutions were represented during the year in the laboratory or on cruises of "Atlantis", Barnard College, Brown University, Cambridge University, Carnegie Institution, Cushman Laboratory for Foraminiferal Research, Flower Medical School, Harvard University, Johns Hopkins University, Lehigh University, Massachusetts Institute of Technology, Queen's University, Royal Military College, Rugers University, Tulane University, University of Michigan, University of Minnesota, University of North Carolina, University of Toronto, U. S. Coast Guard and Yale University.

Captain F. S. McMurray, chief engineer Harold Backus and chief officer T. N. Kelley have continued to give devoted service to the Institution. Messrs. Knute Nielsen, second officer, and O. R. McClunin, assistant engineer, resigned to accept better positions. And Messrs. John Mandly, Jr., and Hans Cook have been appointed in their stead.

Mr. Charles Butcher II had command of "Asterias" during the summer, Messrs. E. Brooks Smith, William Butcher, Richard Bennink and Herbert Schroeder acted as his assistants at different times.

Foreign Travel by the Staff

I attended the meeting of the International Council for the Exploration of the Sea, in July, and was away on leave of absence until October.

Publication

Two numbers of "Papers in Physical Oceanography and Meteorology" appeared, Volume V, numbers 2 and 3.

The following contributions were published between January 1, 1937 and December 31, 1937:

No. 73. Sparrow, F. K., Jr. The Occurrence of Saprophytic Fungi in Marine Muds. Biol. Bull., Vol. LXXIII, No. 2, pp. 242–248. 1937.

No. 91. Roos, S. Edward. Some Geographical Results of the Second Byrd Antarctic Expedition, 1933–1935. I. The Submarine Topography of the Ross Sea and Adjacent Waters. Geog. Rev., Vol. XXVII, No. 4, pp. 574–583. 1937.

No. 93. Ewing, Maurice, A. P. Crary, and H. M. Rutherford. Geophysical Investigations in the Emerged and Submerged Atlantic Coastal Plain. I. Methods and Results. Bull. Geol. Soc. Amer., Vol. 48, No. 6, pp. 753–802. 1937.

No. 107. Smith, Edward H., Floyd M. Soule, Olav Mosby. The "Marion" and "General Greene" Expeditions to Davis Strait and Labrador Sea under Direction of the United States Coast Guard 1928–1931–1933–1934–1935. Scientific Results. Part 2. Physical Oceanography. U. S. Coast Guard Bull., No. 19, pp. i–vi, pp. 1–259. 1937.

No. 111. Renn, Charles E. The Eel-Grass Situation along the Middle Atlantic Coast. Ecology, Vol. 18, No. 2, pp. 323–325. 1937.

No. 112. Clarke, George L. and Donald J. Zinn. Seasonal Production of Zoöplankton off Woods Hole with Special Reference to *Calanus finmarchicus*. Biol. Bull., Vol. LXXIII, No. 3, pp. 464–487. 1937.

No. 118. Seiwell, H. R. Relationship of Minimum Oxygen Concentration to Density of the Water Column in the Western North Atlantic. Gerlands Beiträge zur Geophysik, Vol. 50, pp. 302–306. 1937.

No. 121. Church, Phil E. Temperatures of the Western North Atlantic from Thermograph Records. Publ. Scientifique, No. 4, pp. 1–22. 1937.

No. 123. von Brand, Theodor. Observations upon the Nitrogen of the Particulate Matter in the Sea. Biol. Bull., Vol. LXXII, No. 1, pp. 1–6. 1937.

No. 124. Waksman, Selman A. and Margaret Hotchkiss. Viability of Bacteria in Sea Water. Jour. Bacteriol., Vol. 33, No. 4, pp. 389–400. 1937.

No. 125. Parr, Albert Eide. A Contribution to the Hydrography of the Caribbean and Cayman Seas. Based upon the observations made by the Research Ship "Atlantis," 1933–34. Bull. Bingham Oceanographic Coll., Vol. V, Art. 4, pp. 1–110. 1937.

No. 126. Welsh, J. H. and F. A. Chace, Jr. Eyes of Deep Sea Crustaceans. I. Acanthephyridae. Biol. Bull., Vol. LXXII, No. 1, pp. 57–74. 1937.

No. 127. Redfield, Alfred C., Homer P. Smith and Bostwick Ketchum. The Cycle of Organic Phosphorus in the Gulf of Maine. Biol. Bull., Vol. LXXIII, No. 3, pp. 421–443. 1937.

No. 129. von Brand, Theodor, Norris W. Rakestraw and Charles E. Renn. The Experimental Decomposition and Regeneration of Nitrogenous Organic Matter in Sea Water. Biol. Bull., Vol. LXXII, No. 2, pp. 165–175. 1937.

No. 130. Stetson, H. C. and J. E. Upson. Bottom Deposits of the Ross Sea. Jour. Sed. Petrology, Vol. 7, No. 2, pp. 55–66. 1937.

No. 131. Parker, G. H. Integumentary Color Changes of Elasmobranch Fishes Especially of Mustelus. Proc. Am. Philos. Soc., Vol. 77, No. 3, pp. 223–247. 1937.

No. 132. Fuller, John L. Feeding Rate of *Calanus finmarchicus* in Relation to Environmental Conditions. Biol. Bull., Vol. LXXII, No. 2, pp. 233–246. 1937.

No. 133. Renn, Charles E. Bacteria and the Phosphorus Cycle in the Sea. Biol. Bull., Vol. LXXII, No. 2, pp. 190–195. 1937.

No. 134. Stauffer, Robert C. Changes in the Invertebrate Community of a Lagoon after Disappearance of the Eel Grass. Ecology, Vol. 18, No. 3, pp. 427–431. 1937.

No. 135. Fish, Charles J. and Martin W. Johnson. The Biology of the Zoöplankton Population in the Bay of Fundy and Gulf of Maine with Special Reference to Production and Distribution. J. Biol. Bd. Can., Vol. 3, No. 3, pp. 189–322. 1937.

No. 137. Seiwell, H. R. Short Period Vertical Oscillations in the Western Basin of the North Atlantic. Papers in Physical Oceanography and Meteorology, Vol. V, No. 2, pp. 1–44. 1937.

No. 138. Seiwell, H. R. The Minimum Oxygen Concentration in the Western Basin of the North Atlantic. Papers in Physical Oceanography and Meteorology, Vol. V, No. 3, pp. 1–24. 1937.

No. 139. Seiwell, H. R. The Oxygen-Poor Layer in the Western North Atlantic. Jour. d. Conseil, Vol. XII, No. 3, pp. 277–283. 1937.

No. 140. Rakestraw, Norris W. and Homer P. Smith. A Contribution to the Chemistry of the Caribbean and Cayman Seas. Bull. Bingham Oceanographic Coll., Vol. VI, Art. 1, pp. 1–41. 1937.

No. 141. Rakestraw, Norris W. and Victor M. Emmel. The Determination of Dissolved Nitrogen in Water. Analytical edition Ind. and Eng. Chem., Vol. 9, pp. 1–6. 1937.

No. 142. Seiwell, H. R. Short-Period Variations of Oceanographic Characteristics in the Western North Atlantic. Trans. Am. Geophys. Union, Eighteenth Annual Meeting, pp. 220–222. 1937.

No. 143. Stetson, H. C. Current-Measurements in the Georges Bank Canyons. Trans. Am. Geophys. Union, Eighteenth Annual Meeting, pp. 216–219. 1937.

No. 144. Butler, Margaret Ruth. The Effect of its Nitrogen Content on the Decomposition of the Polysaccharide Extract of *Chondrus crispus*. Biol. Bull., Vol. LXXIII, No. 1, pp. 143–146. 1937.

No. 145. Welsh, J. H., F. A. Chace, Jr., and R. F. Nunnemacher. The Diurnal Migration of Deep-Water Animals. Biol. Bull., Vol. LXXIII, No. 2, pp. 185–196. 1937.

No. 146. Stetson, H. C. and J. Fred Smith. Behavior of Suspension Currents and Mud Slides on the Continental Slope. Am. Jour. Sc., Fifth Series, Vol. XXXV, No. 205, pp. 1–13. 1937.

No. 148. Turner, Abby H. Serum Protein Measurements in the Lower Vertebrates. II. In Marine Teleosts and Elasmobranchs. Biol. Bull., Vol. LXXIII, No. 3, pp. 511–526. 1937.

No. 149. Parr, Albert Eide. On the Longitudinal Variations in the Dynamic Elevation of the Surface of the Caribbean Current. Bull. Bingham Oceanographic Coll., Vol. VI, Art. 2, pp. 1–20, 1937.

No. 150. Riley, Gordon A. The Significance of the Mississippi River Drainage for Biological Conditions in the Northern Gulf of Mexico. Sears Found. Journ. Mar. Res., Vol. I, No. 1, pp. 60–74. 1937.

No. 151. Seiwell, H. R. Consumption of Oxygen in Sea Water under Controlled Laboratory Conditions. Nature, Vol. 140, p. 506. 1937.

No. 153. Montgomery, R. B. A Suggested Method for Representing Gradient Flow in Isentropic Surfaces. Bull. Am. Meteorol. Soc., Vol. 18, pp. 210–212. 1937.

No. 155. Parr, Albert Eide. Report on Hydrographic Observations at a Series of

Anchor Stations across the Straits of Florida. Bull. Bingham Oceanographic Coll., Vol. VI, Art. 3, pp. 1–62. 1937.

No. 156. Lillick, Lois C. Seasonal Studies of the Phytoplankton off Woods Hole, Massachusetts. Biol. Bull., Vol. LXXIII, No. 3, pp. 488–503. 1937.

No. 157. Waksman, Selman A., J. L. Stokes and Margaret R. Butler. Relation of Bacteria to Diatoms in Sea Water. Jour. Mar. Biol. Assoc., Vol. XXII, pp. 359–373. 1937.

No. 158. Spilhaus, Athelstan F. Note on the Flow of Streams in a Rotating System. Sears Found. Journ. Mar. Res., Vol. I, No. 1, pp. 29–33. 1937.

No. 164. Clarke, George L. On Securing Large Quantities of Diatoms from the Sea for Chemical Analysis. Science, Vol. 86, No. 2243, pp. 593–594. 1937.

Coöperation

The coöperative field of activities of the Institution was considerably expanded. During the winter, "Atlantis" continued, in the Caribbean and Gulf of Mexico, the joint survey with the Bingham Oceanographic Foundation of Yale University, Professor Parr acting as scientist in charge, and the Foundation again contributing $1500 toward the expenses of the cruise.

For three weeks off Guantanamo, "Atlantis," in charge of Mr. Iselin, carried on certain hydrographic investigations for the U. S. Navy, which, being of a confidential nature, can be only mentioned here. And this work was continued on a special cruise on the continental shelf in August and September.

During the winter cruise, arrangements were made for Dr. Piggot of the Carnegie Institution of Washington to take bottom cores in deep water near Jamaica. Dr. Piggot also accompanied Mr. Stetson on "Atlantis" cruise #69, when additional cores were obtained on the continental shelf. In September, the facilities of "Atlantis" were again put at the disposal of Dr. Ewing, of Lehigh University, for trials of improved instruments for submarine seismic measurements constructed under a grant to Dr. Ewing by the Geological Society of America.

Finally, the program of joint investigation with the Bermuda Biological Laboratory, of the variations in the North Atlantic drift, mentioned in the Report for 1936 as then under discussion, was commenced in June, and continued on "Atlantis" cruises 72 and 73.

A 78 foot auxiliary ketch purchased in England, during the summer, from the Grant made to the Bermuda Laboratory by the Royal Society, is now refitting, and is expected in Bermuda during the coming spring. The Woods Hole Institution has agreed to provide the general scientific oversight, and Dr. E. F. Thompson, a member of the scientific staff of the "John Murray" expedition to the Indian Ocean has been appointed hydrologist at the Bermuda Laboratory.

The ultimate object is to learn whether or not oceanic circulation changes sufficiently, from year to year, to be an important factor either in the fisheries, on the two sides of the Atlantic or in the climatic variations in northern Europe.

At the suggestion of Professor Hans J. Clarke, of Columbia, and of President J. B. Conant, of Harvard, a net technique was developed by Dr. G. L. Clarke for collecting diatoms in mass, free from larger organisms, for chemical analysis, and an account of this technique was published as Contribution No. 164 from the Laboratory. Large quantities were obtained on two occasions, Professor Clarke's study of which has already yielded results of great interest.

Field Work

Operations of "Atlantis" for the year 1937:

Cruise 65: January–May; Caribbean and Gulf of Mexico.
Cruise 66: June; Bermuda.
Cruise 67: July; South of the Gulf Stream.
Cruise 68: July; South of Georges Banks.
Cruise 69: August; Across the Gulf Stream.
Cruise 70: August; South of Montauk Point.
Cruise 71: September; Across the Gulf Stream.
Cruise 72: October; Bermuda.
Cruise 73: December; Across the Gulf Stream.

Summary of observations:

Total distance sailed, miles	18,157
Number of days at sea	247
Deep hydrological stations	163
Shallow hydrological stations	97
Trawling stations	46
Tows with 2 meter closing nets	21
Other plankton hauls	177
Bottom dredge samples and mud cores	4

"Asterias," as usual, was employed during the summer on short trips, for various scientific purposes near Woods Hole.

Staff Meetings

The regular Staff meetings were held during the summer, at which the following speakers presented papers: C. O'D. Iselin, H. R. Seiwell, R. B. Montgomery, C.-G. Rossby, C. E. Renn, R. C. Murphy, O. E. Sette and A. F. Spilhaus.

Scientific Program

The activities of the various investigators at the laboratory during the past year can be summarized as follows:

Physical oceanography and meteorology. Completion of a report on the physical oceanography of the Labrador Sea based on U. S. Coast Guard cruises; E. H. Smith, Floyd M. Soule.

Preparation of report on oceanographic results of the International Ice Patrol cruises, season of 1936; Floyd M. Soule.

A study of the circulation in the eastern slope water area based on three "Atlantis" hydrographic surveys; Columbus O'D. Iselin, Alfred Woodcock, Kurt Kraus.

Investigation of the periodicity of internal waves in deep water; H. R. Seiwell.

Design of an electric recording current meter; E. E. Watson.

Completion of report on the circulation of the Gulf of Maine, E. E. Watson.

Studies of the origin of the minimum oxygen layer; H. R. Seiwell, Gladys E. Seiwell.

Development of a method for computing gradient flow in isosteric surfaces; Raymond B. Montgomery.

A comparison of observed changes in sea level with the calculated variations in dynamic height; Raymond B. Montgomery.

Measurement of the changing light intensity reaching various depths during the course of each day in connection with a study of the diurnal migration of plankton; G. L. Clarke.

Development of methods for the measurement of light penetration at depths greater than 200 meters and redesign of our photometric apparatus to conform with the recent international agreement; G. L. Clarke, W. R. Sawyer.

The development of methods for studying the variations in the circulation system of the North Atlantic, particularly as they affect the climate and the fisheries; Columbus O'D. Iselin.

Experimental investigation of the effect of rotation and stratification on the mechanics of wake streams and theoretical investigations of the same problem; C.-G. Rossby, A. F. Spilhaus.

Physical and biological chemistry of sea water and of marine sediments. Measurements of the gaseous nitrogen in solution in sea water; V. M. Emmel.

Measurement of the nitrogen content of particulate organic matter in sea water, at different depths and localities; Th. von Brand.

A study of the distribution of oxygen in the Caribbean and the Gulf of Mexico; H. R. Seiwell, C. M. Coker.

Study of the evolution of compounds of nitrogen during the decomposition of organic matter in the sea; N. W. Rakestraw, Th. von Brand, C. E. Renn.

A study of the oxygen consumption in sea water and the estimations of nannoplankton by oxygen demand methods; C. E. Renn.

Bacteriology and biochemistry of ocean muds; S. A. Waksman, M. Hotchkiss, C. L. Carey, Y. Yardman, U. Vartiovaara.

Availability of the organic nitrogen in marine muds; S. A. Waksman, C. E. Renn.

Completion of a report on the special chemistry of the Caribbean and Cayman Seas; N. W. Rakestraw, Homer P. Smith.

Completion of a paper on the determination of dissolved nitrogen in water; N. W. Rakestraw, V. M. Emmel.

Organization of chemical methods for the joint program with the Bermuda laboratory; N. W. Rakestraw, D. Carritt, C. E. Herrick.

Completion of a report on the distribution of phosphorus compounds and of ammonia in the waters of the Gulf of Maine; A. C. Redfield, Homer P. Smith.

Studies of the organic detritus as food for bottom organisms; R. C. Stauffer.

Physiology of marine organisms. Experimental study of the nutrition of copepods; G. L. Clarke, David Bonnet.

Experimental study of the rate of growth of scales of the cod at different temperatures; W. C. Schroeder.

Continued study of the rate of growth and migrations of cod in different parts of the Gulf of Maine, based on scale-studies; W. C. Schroeder.

Continued studies on factors controlling color changes in fishes; G. H. Parker, A. Abramowitz.

Effect of surface on the activity of marine bacteria; S. A. Waksman, M. Hotchkiss.

Photic reactions of copepods in relation to their diurnal migrations; G. L. Clarke, W. H. Johnson.

Study of the assimilation of phosphates and nitrates in relation to photosynthesis in diatoms; B. H. Ketchum.

A study of the reproductive cycle in Limacinae in the Gulf of Maine; S. C. T. Hsiao.

Experimental study of the photophores of live euphausiids; T. H. Waterman.

Effect of adrenaline on urine excretion in marine teleosts; L. A. Toth.

Plankton Studies. The testing of various zoöplankton nets to determine the smallest size suitable for quantitative investigations; G. L. Clarke, Dean Bumpus.

Development of a method for collecting large quantities of diatoms for chemical analyses without undue contamination by other organisms; G. L. Clarke.

Identification of diatoms collected on "Atlantis" cruises in the Gulf of Maine; Lois C. Lillick.

Continued study of seasonal and regional distribution of planktonic animals over the continental shelf, Cape Cod-Chesapeake Bay; H. B. Bigelow, Mary Sears.

Study of the collection and completion of a report on the medusae collected by William Beebe 1929–30 at Bermuda; H. B. Bigelow.

Analysis of a series of closing net hauls made in deep water over a 24 hour period; R. F. Nunnemacher, T. H. Waterman.

Marine microbiology. Morphological and cultural characteristics of bacteria from marine muds; Y. Hardman.

A study of past temperature conditions off the continental slope by means of the identification of the foraminifera fauna deposited at different levels in deep sea mud cores; F. B. Phleger, Jr.

Studies of the bottom-living foraminifera of neighboring waters; Frances Parker.

Submarine geology. Further experimentation in the development of seismic instruments for use on the sea floor; Maurice Ewing.

Further deep water trials of a new explosive coring tube; C. S. Piggot, H. C. Stetson, A. Woodcock.

Further studies of the geological significance of the submarine canyons found at the edge of the continental shelf between Georges Bank and Delaware Bay; H. C. Stetson.

V. STAFF

(As of December 31, 1937)

HENRY B. BIGELOW, Professor of Zoölogy, Harvard University, Director
CORNELIA L. CAREY, Barnard College, Research Associate in Marine Bacteriology
GEORGE L. CLARKE, Tutor and Instructor, Harvard University, Junior Biologist
COLUMBUS O'D. ISELIN, Assistant Professor of Physical Oceanography, Harvard University, and Assistant Curator of Oceanography, Museum of Comparative Zoölogy, Research Associate in Physical Oceanography
A. E. PARR, Director of Peabody Museum and Curator of the Bingham Oceanographic Collection, Yale University, Research Associate in Oceanography
NORRIS W. RAKESTRAW, Associate Professor of Chemistry, Brown University, Research Associate in Physical Chemistry
ALFRED C. REDFIELD, Professor of Physiology, Harvard University, Senior Biologist
C. E. RENN, Tutor in Biology and Instructor in Sanitary Engineering, Harvard University, Junior Marine Bacteriologist
C.-G. ROSSBY, Professor of Meteorology, Massachusetts Institute of Technology, Oceanographer
H. R. SEIWELL, Investigator in Oceanography
FLOYD M. SOULE, Senior Physical Oceanographer, U. S. Coast Guard, Research Associate in Oceanography
HENRY C. STETSON, Research Associate in Paleontology, Museum of Comparative Zoölogy, Research Associate in Submarine Geology.
SELMAN A. WAKSMAN, Microbiologist, New Jersey Agricultural Experiment Station, Marine Bacteriologist
E. E. WATSON, Assistant Professor of Physics, Queen's University, Research Associate in Physical Oceanography
CAPTAIN SIR HUBERT WILKINS, Honorary Research Associate in Oceanography
DEAN F. BUMPUS, Biological Technician
DAYTON E. CARRITT, Chemical Technician
ALFRED WOODCOCK, Oceanographic Technician

WILLIAM C. SCHROEDER, Business Manager
MRS. VIRGINIA WALKER SMITH, Secretary and Administrative Assistant
WILLIAM SCHROEDER, Superintendent of Buildings and Grounds

APPENDIX

Reports of progress by investigators working at the Institution during 1937.

EFFECT OF TEMPERATURE ON GROWTH OF COD, AND OF THEIR SCALES

HENRY B. BIGELOW AND WILLIAM C. SCHROEDER

Codfish were held in tanks having a constant temperature of 5° and 14° C., respectively. In 70 days, from May 18 to July 27 the cold water fish (11 specimens) increased 1.51 cms. in total length from an average of 36.36 cms. to 37.87 cms. and the warm water cod (13 specimens) 1.93 cms. from an average of 38.27 cms. to 40.20 cms. Beyond July 27 the number of fish remaining was too small to show convincing results but by September 17, or 122 days later, 8 cold water cod showed an average increase of 3.00 cms. as against 3.38 cms. for 4 warm water cod.

The food consumed during the first 70 days by the 5° fish was slightly less (av. 0.9 clams per fish per day) than by the 14° fish (av. 1.2 clams per day).

Although it was expected that the scales of the warm water fish might produce the widely spaced circuli of summer growth and the cold water fish the narrowly spaced circuli of winter growth, both lots of fish at the end of the experiment had narrow or medium narrow peripheral circuli, a condition which probably resulted from keeping them in such close confinement.

ZOÖPLANKTON STUDIES

HENRY B. BIGELOW AND MARY SEARS

1. The report on the Bermudian medusae collected by Dr. William Beebe, 1929–1930 was completed and submitted for publication.

2. Studies of the waters of the continental shelf, Cape Cod to Chesapeake Bay. Zoöplankton. The final report is in preparation.

3. The report on the Siphonophorae of the "Thor" Expedition to the Mediterranean, 1908–1910 appeared in March.

PENETRATION OF LIGHT INTO THE SEA, FEEDING OF COPEPODS, PLANKTON STUDIES, AND IMPROVEMENTS IN TECHNIQUE FOR QUANTITATIVE COLLECTION OF PLANKTON

GEORGE L. CLARKE

1. Measurements of light penetration were made at 8 stations in the Caribbean Sea region and in the Gulf of Mexico. At the stations in shallow water east of the Mississippi Delta considerable turbidity was encountered in the surface layers. But at the offshore stations in the Gulf and at all the other stations the water was found to be highly uniform and extremely transparent. The observations at the station in the Cayman Sea west of Jamaica revealed the presence of the clearest ocean water ever measured.

During the summer the photometric apparatus was modified to conform to the specifications prepared by the Subcommittee on Submarine Illumination of the International Council for the Exploration of the Sea. (With the collaboration of Dr. W. R. Sawyer)

Measurements of transparency of the water and of the intensity of daylight at the surface were made throughout the 4-day station occupied in the "Slope Water" area for the purpose of investigating the vertical diurnal migrations of the macroplankton.

2. Experiments on the nutrition of copepods were continued, with the assistance of Mr. D. D. Bonnet. The necessity of a minimal food supply in order that moulting take place in Calanus was demonstrated. The suggestion, made by Gross, that the warming of the cultures during the daily inspection period would result in high mortality was carefully tested and found not to be the case. Several diatoms and green flagellates were brought under culture and their chemical composition investigated. (With the collaboration of Dr. Th. von Brand)

3. Investigation of seasonal productivity of coastal and oceanic areas was begun at standard stations in the Coastal Water, Slope Water and Sargasso Water, selected as typical of large bodies of water. The effects of the attendant environmental conditions are being observed from data on the hydrography and chemistry of the water, on the occurrence of nannoplankton, and on the progress of decomposition, etc., which are obtained by collaborating members of the staff.

4. Comparative simultaneous tests with nets of different sizes having shown that a mouth opening as small as 5 inches in diameter

may be expected to yield representative samples of plankton organisms up to the size of copepods, an experimental model has been constructed of a small device for obtaining quantitative plankton samples rapidly and under all weather conditions. The device is opened and closed by messengers, contains a current meter and is provided with a demountable cone of netting, and is usable in series.

A 5″ current meter was also developed in which the response is linear for speeds ranging from $\frac{1}{4}$ to 3 knots and which is therefore suitable for measuring the flow of water through the mouth of a small plankton net.

THE PHYSIOLOGY OF REPRODUCTION IN THE DOGFISH, MUSTELUS CANIS

FREDERICK L. HISAW AND ALEXANDER A. ABRAMOWITZ

A preliminary study of the physiology of reproduction in Elasmobranchs has been made in the smooth and in the spiny dogfish, *Mustelus canis* and *Squalus acanthias*. Mustelus, being the more favorable for such an investigation, received most attention. Growth, maturity, ovulation, placentation, duration of pregnancy, or, in general, the natural history of this dogfish were first studied.

Parturition in Mustelus occurs during late May and early June, about sixteen pups 35 cms. in length being born in a litter. Our present opinion is that female pups having grown 20–30 cms. a year become sexually mature at the end of the third or fourth year. All females below 95–100 cms. in length and males under 70–80 cms. are sexually immature. In females measuring about 90 cms. the ovary contains numerous small follicles, and the distal portion of the Mullerian duct has become transformed into a small uterus. In the spring of the following year, these females (95–100 cms. or more in length) become fully mature: the ovary contains 16–20 large, yellow ova and the uterus and oviducal gland are fully developed. In late June and early July, ovulation and fertilization take place and usually each uterine horn contains about eight embryos. Following ovulation, the oviducal gland atrophies. The embryos grow very rapidly from July to September, a period which may be considered as a protracted ovo-viviparous condition. By September, the growth of the embryos has proceeded at such a pace that the yolk has entirely disappeared and the placenta is formed. The placenta is firmly attached to the uterus and closely associates the maternal and foetal circulations. The embryos at this stage are about 15 cms. in length. Pregnancy apparently lasts until the following spring (ten months in all) when parturition occurs. Meanwhile, another wave of oogenesis has taken place during fall and winter so that 16–20 or more mature ova are present when the dogfish again migrate into Buzzards Bay and Vineyard Sound in the spring. Ovulation, fertilization, and pregnancy occur, and the cycle is repeated. Growth in females apparently falls off soon after sexual maturity is attained, for we have never caught animals above 130 cms. in length.

The physiological investigation has been concerned with the regulative processes of parturition and ovulation, pituitary-gonadal interrelationships in both sexes, effect of castration on uterine development, effects of purified mammalian gonadotropic hormones on the gonads and other endocrine glands of sexually immature animals and pups, qualitative analysis of the hormone content of dogfish pituitary tissue, and chemical extraction of the hormones of the testes and of the follicular and luteal portions of the ovary.

HYDROLOGICAL INVESTIGATIONS

COLUMBUS O'D. ISELIN

At the request of the U. S. Navy a detailed investigation of the surface layer was made in February off Guantanamo, Cuba, and in August for six areas south of Long Island, New York. From the oceanographic standpoint the observations have proved to be of considerable interest and it is hoped that they can be continued periodically throughout the coming year in connection with the Bermuda project.

In April, I visited Bermuda for a week to confer with Dr. Wheeler concerning the details of this coöperative investigation. The observations from the "Atlantis" on the Montauk Point-Bermuda section began in June and now five series of data have been corrected and studied in a preliminary way.

During the summer with the assistance of Mr. Kurt Kraus the three slope water surveys made in 1936 were worked up and the diagrams prepared. Although Mr. Woodcock has spent more of his time at sea, the station cards and the filing of the station sheets are nearly up to date. At the end of the year about 500 water samples remain untitrated.

THE REACTIONS OF ADULT FEMALE CENTROPAGES TYPICUS TO LIGHT AND GRAVITY

W. H. JOHNSON AND J. E. G. RAYMONT

Experiments were carried out to determine the responses of this copepod to changes in light intensity. The animals were obtained by means of plankton nets in the Sound off Woods Hole. Identification was made by means of a binocular microscope in the diffuse daylight of the laboratory. The copepods were then sealed within large glass cylinders, the glass end of which enabled light to enter from either end, so that frequent reversal of the tubes made the results more reliable. The animals were exposed for different periods of time to various light intensities ranging from ca 0.0007 footcandles to a high of that of bright noon sunlight.

The copepods were found to be primarily photopositive over the whole range of intensities used. After prolonged exposure to the highest intensity employed, however, a considerable number of animals were repelled. A decrease in light intensity then, always resulted in increased attraction. Increase in intensity had apparently no effect. The animals were strongly negatively geotropic in darkness. When geotropism and phototropism were opposed, the reaction depended on the light intensity.

STUDIES ON THE PRODUCTIVITY OF MICROPLANKTON IN THE GULF OF MAINE

LOIS C. LILLICK

Examination of the microplankton collections taken in connection with Dr. Redfield's work in the Gulf of Maine during 1933 and 1934 has been completed. Distribution of the plankton, both qualitative and quantitative, in relation to the physical and chemical conditions of the water is being considered, with a view toward a possible explanation of phytoplankton productivity in the Gulf, a preliminary examination seeming to indicate that none of the theories advanced in the past is sufficient to account for the production of plankton in this area. A general report is in preparation.

STUDIES ON VERTICAL MIGRATIONS OF BATHYPELAGIC ORGANISMS

R. F. NUNNEMACHER AND T. H. WATERMAN

Stimulated by the interesting results of previous studies on vertical migration made from "Atlantis," a more thorough investigation was undertaken in 1937. Material was collected in the waters of the continental slope by means of closing-net hauls made over a twenty-four hour period, at depths of 200, 400, 600, 800 and 1,000 meters. The balance of the summer was spent in identifying and counting the specimens of the hauls. Dr. Fenner Chace, Jr., greatly assisted us in this work by identifying the Crustacea. Some new species of Ceratiid fish were discovered in the catches and their taxonomy and anatomy are being studied in some detail by Talbot H. Waterman.

A preliminary analysis of the data indicated that the vertical distribution of many of the forms showed changes from one haul to the next. These changes seemed in a number of cases to involve a downward movement of the center of population during the daylight hours and a corresponding upward movement at night. This was most evident in some of the larger and presumably more actively swimming crustacea. Because of the differences in the behavior of various forms these changes in vertical distribution cannot be explained merely on the basis of mass movements of the water column.

The identification and counting, together with the analysis of the total data are being carried forward.

STUDIES OF COLOR CHANGES IN THE SMOOTH DOGFISH, MUSTELUS CANIS

G. H. PARKER

During the spring and summer, color changes were studied in young dogfish. Findings are that these animals became pale not only in consequence of nerve action but also because of loss of intermedin from their blood. There was no evidence of a W-substance as suggested by Hogben. Their blood carried nothing that induced blanching. The crude concentrated lipohumor produced by their nerves was effective in blanching the fish even after this substance had been kept in the dried state in the laboratory for a year.

This humor must be a very stable substance. When injected into catfish and into frogs, it induces a darkening, quite a reverse of the effect on the smooth dogfish.

The details of these experiments are in process of publication in the Proceedings of the American Philosophical Society.

CHEMICAL INVESTIGATIONS

NORRIS W. RAKESTRAW

With the appointment of Mr. Dayton Carritt as full time chemical technician, much of the attention of this department has been directed towards outlining and organizing the chemical program to be carried out in connection with the coöperative survey of the Gulf Stream. The summer was partly spent in the perfection of methods and technique for this work. Early in the fall this program was initiated and results have already been accumulated from two or three cruises. The effort is being made to get as complete a picture as possible of the chemical cycle in the water through the various seasons, as it affects the compounds of hydrogen, phosphorus and carbon. Routine analyses are being carried out for nitrate, nitrite, ammonia and plankton nitrogen, phosphate, organic phosphorus, and plankton phosphorus; pH, and alkalinity, from which, along with temperature and salinity determinations, the various carbon dioxide functions will be calculated. With the oxygen determinations and those for "biological oxygen demand" a fairly complete chemical picture should be obtained. Samples will also be brought back from these cruises for the determination of gaseous dissolved nitrogen and the inert gases.

Mr. Emmel has continued his work of the last two years on the determination of gaseous dissolved nitrogen. The details of the method which was eventually worked out have been published, and slight changes in the procedure have made it possible to get a fairly accurate estimate of argon, as well as nitrogen. The results from several stations are now completed and will shortly be published. It was found that the data for solubility of nitrogen in sea water heretofore reported in the literature, are not accurate and we have redetermined the solubility by the use of this method in sea waters varying in chlorinity from 16–20°/₀₀ and in temperature from 0–30°.

Gaseous dissolved nitrogen in stored samples of sea water has been followed for more than a year, but this work is being repeated with some modifications. We are not yet in a position to be certain whether nitrogen undergoes any change on standing.

Mr. C. E. Herrick was engaged during the summer in the construction of a photoelectric colorimeter for use in the routine analytical methods. Although difficulties were encountered in making the apparatus suitable for work on shipboard, it seems evident that these will ultimately be overcome. Mr. Herrick is now undertaking a study of the distribution of the inert gases in sea water.

STUDIES ON THE BIOLOGY OF THE GULF OF MAINE, AND OF THE PHYSIOLOGY OF DIATOMS

ALFRED C. REDFIELD

1. A study of the distribution of *Limacina retroversa* in the Gulf of Maine during the season 1933–34 is in preparation. Analysis of the size distribution of the catches shows that two well-distinguished invasions of Limacina occurred, in December–January and April–May respectively. In both cases the organisms appeared in the eastern part

of the Gulf as small individuals. In the case of the early winter invasion the course of their drift was followed until they arrived in the western part of the Gulf as fully grown individuals in April and May.

2. Mr. Sidney Hsiao has completed a study of the development of the reproductive system, spermatogensis and sex-reversal of *Limacina retroversa*, based on these collections. The smaller individuals taken are sexually undifferentiated. The male tissue of the gonad develops first. When the animals are 0.5 mm. in diameter the ratio of the predominant sex is 16 males to 1 female. As the size increases the proportion of ovarian tissue becomes greater and equals that of the spermatic tissue when the diameter is 2 mm. The population which entered the Gulf in the winter of 1933–34 consisted of small individuals of which the sexually differentiated ones were predominantly males. Of these the smaller 20 per cent are without female tissue in the gonad. Between January and April these protandric individuals appear to become hermaphroditic, with an increasing proportion of female tissue in the gonad. Spermatozoa are produced by the small males in the winter and by the hermaphroditic males at all times. Eggs are spawned first in April and continue to be produced throughout the summer. Mature ova do not appear until the animals reach a diameter of 1.3 mm.

The population which entered the Gulf in April and May shows a different sexual history. Sexual differentiation begins at a smaller size, as does also the development of female tissue.

3. Robert C. Stauffer was concerned during the summer of 1937 with the evaluation of some of the invertebrate communities on soft bottom in Buzzards Bay, Lackey's Bay, and Tarpaulin Cove, and with analysis of detritus collected in Tarpaulin Cove to determine the rate of accumulation of nitrogenous materials in an attempt to correlate this with the abundance and mass of animals found there.

Sufficient faunal collections were made to indicate the general characteristics of three soft bottom invertebrate communities differing both in biomass and in characteristic species. In regard to detritus accumulation, further data will be needed before any conclusions can be drawn.

4. Bostwick H. Ketchum has developed a satisfactory method of growing the diatom, *Nitzschia closteridium*, in large quantities. Using this source of material, studies have been made on phosphorus metabolism in its relation to photosynthesis. It is found that cultures grown in the light after the exhaustion of phosphorus from the medium continue to multiply, but acquire a definite phosphorus deficiency or "debt." On removing such cultures from the light and

supplying phosphate, a rapid absorption of phosphate occurs until the deficiency is made up, after which no further phosphorus assimilation takes place.

STUDIES OF CURRENT STRUCTURE

C.-G. ROSSBY

During the past year a number of experiments were carried out by A. F. Spilhaus for the purpose of determining the modifications produced by the Coriolis' force on the structure of wake streams. G. T. Taylor had expressed the opinion that in purely two-dimensional current systems the effects of the Coriolis' force are eliminated by the establishment of a balancing pressure field. It was definitely established that this is not the case but that in every instance a marked modification in the flow pattern is produced by the rotation. The anticyclonic flow patterns obtained are too complicated for theoretical analysis but have been suggestive and of considerable help in the interpretation of the flow patterns obtained on the isentropic charts for the summer season in the United States.

Considerable progress has been made during the year in the theoretical analysis of the effects of lateral frictional forces on idealized current systems. These results will be published during the summer of 1938.

THE PENETRATION OF LIGHT INTO THE SEA

W. R. SAWYER

It has been shown that the vertical migrations of macroplankton take place in the Sargasso Sea to depths of at least 800 meters. In order to obtain a quantitative correlation between the light intensity, the depth, and the plankton density, a special deep-sea photometer was designed to obtain measurements to a depth of 1000 meters in these waters. The instrument could not be built in time to obtain measurements during the summer.

The rectifier or barrier layer type of photoelectric cell is now used extensively in ecological photometers. These cells are known to have a considerable temperature coefficient. A method of correcting for this was worked out and applied to the measurements made during the summer by Dr. Clarke. It was found that serious errors can arise if such corrections are not taken into consideration.

Data on the photosensitivity, non-linearity of response, temperature coefficient, and fatigue were obtained for the Photox, Photronic, and Lange cells. The Lange cells tested were considerably more sensitive than the others. The Photox cells showed a serious change in sensitivity with use.

STUDIES OF THE MINIMUM OXYGEN CONCENTRATION, OF SUBMARINE VERTICAL OSCILLATIONS, AND OF RELATED PROBLEMS IN THE NORTH ATLANTIC

H. R. SEIWELL

1. The problem of the origin of the minimum oxygen concentration in the North Atlantic has been studied from the point of view of the biochemical and physical mechanisms operating at mid depths with the assistance of Mr. Coit M. Coker. This has involved analysis of existing field observations in conjunction with information obtained from planned laboratory experiments.
2. Studies on the rates of settling of decomposing organic material in stratified sea water have been undertaken at Woods Hole and Bermuda in collaboration with Gladys Eddy Seiwell.
3. Investigation of the distribution of oxygen and its application to the physical oceanography of the Caribbean Sea region (based on the 1933 and 1934 "Atlantis" observations) was completed. In this work I was assisted by Mr. Coit M. Coker with whom the results of a joint investigation of the minimum oxygen concentration in the Caribbean region is in preparation for publication.
4. An inquiry into the causes and nature of submarine vertical oscillations in the western North Atlantic, begun last year, has been continued as a problem of major importance. Results of the analysis of investigations at the 1936 eight day station (mid way between the Gulf Stream and Bermuda) have been published as contributions number 137 and 142; additional data on the phenomenon were obtained at two other stations (of 2 and 8 days duration) in the same locality in June, 1937.

PHYSICAL OCEANOGRAPHY OF THE GRAND BANKS REGION AND LABRADOR SEA

FLOYD M. SOULE

During the months of January and February the analysis of data collected on the 1935 post-season cruise was continued and the problem of lateral mixing along the margins of the Labrador and Atlantic Currents was attacked through the medium of investigation of vertical sections of vertical stability. The months of April, May and June were spent on the oceanographic vessel of the International Ice Patrol, the U. S. C. G. Patrol Boat "General Greene," in the region of the Grand Banks, supplying topographic dynamic charts of the region to the Ice Patrol cutters "Champlain" and "Mendota." During this period three current surveys of the critical area were made with reference to the 1,000 decibar surface; while the temperature and salinity measurements extended in many cases to 1400 meters, where the depth of water permitted. In this work 201 oceanographic stations were occupied. Between June 21 and July 12 an additional 75 oceanographic stations were occupied on a post-season cruise which involved six sections approximately normal to the Labrador and Atlantic Currents and designed to cross their common boundary at intervals from the Tail of the Grand Banks to northeast of Flemish Cap. The temperature and salinity measurements made on the post-season cruise extended from the surface to 2000 meters and in the region southwestward of Flemish Cap the measurements extended to as near bottom as was practicable. On the post-season cruise 843 sonic soundings were taken. These soundings have been corrected, tabulated and supplied to the U. S. Hydrographic Office and to the International Hydrographic Bureau.

In continuation of the study of the common boundary between the Labrador and Atlantic Currents, a new criterion has been developed to supplant the "cold wall," which is a superficial temperature phenomenon. This criterion is essentially a horizontal projection of the zero salinity anomaly surface at the level of the intermediate anomaly maximum. Some advance has also been made in the study of factors which modify the iceberg forecast formula developed by Smith and currently in use.

The work of preparing for publication the oceanographic section of the U. S. Coast Guard Bulletin No. 27 (season of 1937) is in progress.

STUDIES IN SEDIMENTATION AND ON THE GEOLOGY OF THE CONTINENTAL SHELF

H. C. STETSON

Work has been started on the problem of the Pleistocene history of the Atlantic Basin in collaboration with Dr. J. A. Cushman, Dr. F. B. Phleger, and Miss Frances L. Parker. Two years ago Dr. C. S. Piggot obtained a line of cores from Newfoundland to Ireland, which are at present being worked up by the U. S. Geological Survey. So slow has been the rate of sedimentation that the whole of the Pleistocene column is represented, and the cores have yielded a great deal of information concerning the glacial and interglacial stages. The preliminary results were so unexpected and so important, it was decided to supplement this single line with others crossing the Gulf Stream farther to the south, tying in conditions of sedimentation in the ocean basin proper with those of the continental margins. As an essential part of this program Dr. Phleger is working on the foraminifera of the slope cores taken down to 2000 fathoms in 1936, and will continue with those obtained last summer. Dr. Cushman and Miss Parker are working up the foraminifera from the surface sediments of the continental shelf from the samples obtained for me by "Atlantis" several years ago. Several traverses were run from the shore to the break in slope, with closely spaced stations, from Cape Cod to Cape Canaveral. At present much confusion exists as to faunal ranges, which forms are restricted to shallow and which to deep water, and similar matters, because our knowledge of the modern foraminifera rests on scattered samples spotted hit or miss over the shelf. If foraminifera are to be used effectively for correlation purposes in the deep cores, these matters must be settled.

Tank experiments were carried out as to the effectiveness of Daly's mud-suspension currents as a means for the distribution of terrigenous sediment away from the land mass into the ocean basin, and the results published.

The report on the sediments of the continental shelf is nearing completion, and is to be published as part of a symposium on marine sediments projected by the Committee on Sedimentation of the National Research Council.

EFFECT OF EPINEPHRINE ON RATE OF WATER EXCRETION IN THE PUFFER (SPHEROIDES MACULATUS)

LOUIS A. TOTH

In a series of experiments carried out on the puffer (*Spheroides maculatus*) anaesthetized with urethane, intravenous injections of epinephrine varying from 3 to 240 micrograms per 100 grams body weight resulted in polyuria. The arterial blood pressure increased significantly after the injections. Control experiments with 25 per cent sea water had only a slight and transitory effect on the urine excretion and blood pressure.

The urine rate was studied by exposing and cannulating one ureter and observing the movement of the urine meniscus in the cannula. The blood pressure was recorded by cannulating an artery and connecting the artery to a small mercury manometer.

NITROGEN DETERMINATIONS OF THE PARTICULATE MATTER IN THE SEA

THEODOR VON BRAND

Continuing last year's investigations, determinations on four deep stations have been performed. Two stations were located in the Sargasso Sea, one in the Slope water and one in the Caribbean Sea. The greatest variations of the particulate nitrogen were found in the upper 400 m, the zone of greatest biological activities. In the deeper and deepest layers the absolute values were lower than in the upper layers, and the variations were much smaller. It seems now definitely proved that in those parts of the sea so far investigated, nitrogen is present everywhere in particulate form in such amounts as to allow fairly accurate determinations.

STUDIES IN MARINE MICROBIOLOGY

SELMAN A. WAKSMAN, CHARLES E. RENN, CORNELIA L. CAREY,
MARGARET HOTCHKISS, YVETTE HARDMAN, UNTO
VARTIOVAARA, ASSISTED BY R. L. HERVEY

The following studies in Marine Microbiology were made during 1937: 1. Chemical and biological oxidation of organic matter in the sea bottom and the rôle of bacteria in these processes. 2. Adsorption of bacteria by marine bottom material. 3. Liberation of ammonia in the decomposition of marine organic residues and of bottom material. 4. Occurrence of nitrite and nitrate forming bacteria in sea water and in the sea bottom. 5. Occurrence of nitrogen-fixing bacteria in the sea bottom. 6. Quantity, distribution, and availability of nitrogen in marine muds. 7. Distribution of available organic matter in deep sea water. 8. Coöperative investigation with Dr. von Brand and Dr. Rakestraw upon the nitrogen cycle in the sea and controlling conditions.

A method for the study of the rate of oxidation of organic matter in bottom material was developed. As measured by the rate of oxygen consumption, organic matter in different types of marine bottoms varies in quantity, distribution, and biological availability. Some oxygen is taken up by direct chemical action of the organic matter but the greater part is consumed during the bacterial decomposition of the latter. Organic matter in sandy bottoms consumes less oxygen directly than that in muds. Deep sea muds contain relatively resistant organic material. The organic matter in sea water and in plankton decomposes much more rapidly than that in mud. Very little nitrogen is made available in the initial stages of decomposition when the rate of oxygen consumption is high (Waksman and Hotchkiss).

The adsorption of marine bacteria in pure culture and in mixed populations by marine bottom was studied in detail. Mud was found to have a marked adsorbing effect upon pure cultures of bacteria as well as upon mixed populations. In the case of the latter, however, the adsorption was soon followed by active bacterial multiplication. Sand bottom had no adsorptive effect upon the bacteria but greatly favored their multiplication (Waksman and Vartiovaara).

In the study of the decomposition of asparagine in sea water by bacteria, it was found that the nitrogen is liberated very rapidly as ammonia, to the extent of 85 per cent in 4 days. A certain part of the carbon and of the nitrogen was changed into bacterial cell substance. A marked correlation was shown to exist between bacterial multiplication, as determined by the plate and microscopic methods, oxygen consumption and ammonia liberation. Results very similar to those found in the case of asparagine were also obtained in the decomposition of *Calanus finmarchicus* in sea water by bacteria. The ratio of the carbon content to the nitrogen liberated as ammonia, or of the carbon to the oxygen consumed in the decomposition process, or of the nitrogen liberated to bacterial multiplication were very similar both in the case of the Calanus and of the asparagine.

Dr. Hotchkiss also continued her observations of the occurrence of Clostridium, or the anaerobic nitrogen-fixing organism in the sea bottom, at different distances from shore.

Dr. Carey devoted most of her time to the study of methods for isolating nitrifying bacteria from the sea and to a study of their occurrence in the water, in the plankton and in the bottom material.

Miss Hardman made a series of observations on the utilization of attachment slides for the study of marine bacteria.

During the summer, the "Asterias" made a series of core sample stations in the Gulf of Maine. Dr. Renn studied the vertical distribution of organic nitrogen in these as a preliminary step in determining the availability of nitrogen at different depths in the mud. It was necessary to develop micro-methods for estimating small quantities of nitrogen in the superficial layers of mud.

Some experiments involving the oxygen consumption of water filtered under carefully controlled conditions show that the nannoplankton represents the large part of the labil organic matter in inshore and harbor water. The proportion varies seasonally. A program to study this relationship in the deep sea was begun.

In coöperation with Dr. von Brand and Dr. Rakestraw, Dr. Renn made a laboratory investigation on the decomposition and regeneration of nitrogen in sea water. Fixed quantities of pure cultures of diatoms decomposed to yield equivalent quantities of ammonia, nitrite, and nitrate in distinct, cyclic sequence. Under illumination the diatoms assimilated the nitrate into equal amounts of organic nitrogen. The cycle of decomposition and regeneration repeated several times in the same system without immobilization of nitrogen. Anaerobic conditions retard plankton decomposition and completely suppress production of soluble inorganic nitrogen compounds.

DIRECT MEASUREMENT OF CURRENTS

E. E. WATSON

The increasing need for direct current measurements is being felt in several branches of oceanographic investigation. In particular the conditions of flow at the lower boundary layer are practically unknown except by surmise and analogy. The only reliable and moderately priced current meter is the Ekman meter, and readings with this instrument are extremely slow, since it has to be hauled up to the deck for each individual reading. A new type of electrically recording meter is being developed, suitable for use at all depths. The machine was completed in preliminary form during the summer and given several trials at rather shallow depths. These trials were sufficient to indicate the weakest points of the design, and certain parts are being modified and rebuilt. The design necessarily includes features which can only be tested under actual conditions at sea.

List of Contributions

LIST OF CONTRIBUTIONS

FROM THE WOODS HOLE OCEANOGRAPHIC INSTITUTION

No. 1. H. U. Sverdrup. Scientific Results of the *Nautilus* Expedition, 1931, under the Command of Captain Sir Hubert Wilkins. I. Introduction and Narrative. *Papers in Physical Oceanography and Meteorology*, Vol. II, No. 1, pp. 3–15. 1933.

No. 2. H. U. Sverdrup. Scientific Results of the *Nautilus* Expedition, 1931, under the Command of Captain Sir Hubert Wilkins. II. Oceanography. *Papers in Physical Oceanography and Meteorology*, Vol. II, No. 1, pp. 16–63. 1933.

No. 3. Floyd M. Soule. Scientific Results of the *Nautilus* Expedition, 1931, under the Command of Captain Sir Hubert Wilkins. III. Echo-Sounding. *Papers in Physical Oceanography and Meteorology*, Vol. II, No. 1, pp. 65-76. 1933.

No. 4. B. Villinger. Scientific Results of the *Nautilus* Expedition, 1931, under the Command of Captain Sir Hubert Wilkins. IV. Die Schweremessungen auf der *Nautilus* Expedition, 1931. *Papers in Physical Oceanography and Meteorology*, Vol. II, No. 3, pp. 3-16. 1933.

No. 5. Henry C. Stetson. Scientific Results of the *Nautilus* Expedition, 1931, under the Command of Captain Sir Hubert Wilkins. V. The Bottom Deposits. *Papers in Physical Oceanography and Meteorology*, Vol. II, No. 3, pp. 17-37. 1933.

No. 6. Selman A. Waksman and Cornelia L. Carey. Rôle of Bacteria in the Decomposition of Plant and Animal Residues in the Ocean. *Proc. Soc. Exper. Biol. and Med.*, Vol. XXX, pp. 526–527. 1933.

No. 7. Arda A. Green and Raymond W. Root. The Equilibrium between Hemoglobin and Oxygen in the Blood of certain Fishes. *Biol. Bull.*, Vol. LXIV, pp. 383-404. 1933.

No. 8. Norris W. Rakestraw. Studies on the Biology and Chemistry of the Gulf of Maine. I. Chemistry of the Waters of the Gulf of Maine in August, 1932. *Biol. Bull.*, Vol. LXIV, pp. 149-158. 1933.

No. 9. H. H. Gran. Studies on the Biology and Chemistry of the Gulf of Maine. II. Distribution of Phytoplankton in August, 1932. *Biol. Bull.*, Vol. LXIV, pp. 159-182. 1933.

No. 10. Selman A. Waksman, H. W. Reuszer, Cornelia L. Carey, Margaret Hotchkiss, and C. E. Renn. Studies on the Biology and Chemistry of the Gulf of Maine. III. Bacteriological Investigations of the Sea Water and Marine Bottoms. *Biol. Bull.* Vol. LXIV, pp. 183-205. 1933.

No. 11. Arda A. Green and Alfred C. Redfield. On the Respiratory Function of the Blood of the Porpoise. *Biol. Bull.* Vol. LXIV, pp. 44-52. 1933.

No. 12. Selman A. Waksman. On the Distribution of Organic Matter in the Sea Bottom and the Chemical Nature and Origin of Marine Humus. *Soil Sci.*, Vol. XXXVI, No. 2, pp. 125-147. 1933.

No. 13. A. C. Redfield. The Evolution of the Respiratory Function of the Blood. *Quart. Rev. Biol.*, Vol. VIII, No. 1, pp. 31-57. 1933.

No. 14. C. O'D. Iselin, II. Some Phases of Modern Deep-Sea Oceanography with a Description of some of the Equipment and Methods of the newly formed Woods Hole Oceanographic Institution. *Annual Report, Smithsonian Institution*, for year ending June 30, 1932, pp. 251-267. (Publication 3198.) 1933.

No. 15. E. Monroe Harwood and Charles F. Brooks. Monthly Sequence of Sea-Surface Temperature on the New York–San Juan Steamship Route. *Trans. Am. Geophys. Union, Fourteenth Annual Meeting*, pp. 173-180. 1933.

No. 16. Alfred C. Redfield and Elizabeth N. Ingalls. The Oxygen Dissociation Curves of some Bloods containing Hemocyanin. *Jour. Cell. and Comp. Physiol.*, Vol. III, No. 2, pp. 169-202. 1933.

No. 17. Selman A. Waksman, Cornelia L. Carey, and Herbert W. Reuszer. Marine Bacteria and their Rôle in the Cycle of Life in the Sea. I. Decomposition of Marine Plant and Animal Residues by Bacteria. *Biol. Bull.*, Vol. LXV, pp. 57-78. 1933.

No. 18. Selman A. Waksman, Margaret Hotchkiss, and Cornelia L. Carey. Marine Bacteria and their Rôle in the Cycle of Life in the Sea. II. Bacteria concerned in the Cycle of Nitrogen in the Sea. *Biol. Bull.*, Vol. LXV, pp. 137-167. 1933.

No. 19. Herbert W. Reuszer. Marine Bacteria and their Rôle in the Cycle of Life in the Sea. III. The Distribution of Bacteria in the Ocean Waters and Muds about Cape Cod. *Biol. Bull.*, Vol. LXV, pp. 480-497. 1933.

No. 20. John Colman. The Woods Hole Oceanographic Institution: Sonic Soundings, and an Account of a Winter Cruise to the Somers Islands. *The Geographical Journal*, Vol. LXXXII, pp. 326-336. 1933.

No. 21. John H. Welsh. Light Intensity and the Extent of Activity of Locomotor Muscles as Opposed to Cilia. *Biol. Bull.*, Vol. LXV, pp. 168-174. 1933.

No. 22. Alfred C. Redfield. The Haemocyanins. *Biol. Rev.*, Vol. IX, No. 2, pp. 175-212. 1934.

No. 23. Selman A. Waksman. The Rôle of Bacteria in the Cycle of Life in the Sea. *Scientific Monthly*. Vol. XXXVIII, pp. 35-49. 1934.

No. 24. H. R. Seiwell. The Annual Organic Production and Nutrient Phosphorus Requirement in the Tropical Western North Atlantic. *Jour. d. Conseil*, Vol. X, No. 1, pp. 20-32. 1935.

No. 25. H. R. Seiwell and G. E. Seiwell. Über den Gesamtphosphorgehalt des Seewassers im westlichen Nordatlantischen Ozean. *Annalen der Hydrographie und Maritimen Meteorologie*, Vol. LXII, pp. 7-13. 1934.

No. 26. George L. Clarke. Observations on the Penetration of Daylight into Mid-Atlantic and Coastal Waters. *Biol. Bull.*, Vol. LXV, pp. 317-337. 1933.

No. 27. C. O'D. Iselin. The Development of our Conception of the Gulf Stream. *Trans. Am. Geophys. Union, Fourteenth Annual Meeting*, pp. 226-231. 1933.

No. 28. August Krogh. A Method for the Determination of Ammonia in Water and Air. *Biol. Bull.*, Vol. LXVII, pp. 126-131. 1934.

No. 29. Norris W. Rakestraw and Frank B. Lutz. Arsenic in Sea Water. *Biol. Bull.*, Vol. LXV, pp. 397-401. 1933.

No. 30. Alfred C. Redfield. On the Proportions of Organic Derivatives in Sea Water and their Relation to the Composition of Plankton. *James Johnstone Memorial Volume, University of Liverpool*, pp. 176-192. 1934.

No. 31. Philip H. Mitchell and Norris W. Rakestraw. The Buffer Capacity of Sea Water. *Biol. Bull.*, Vol. LXV, pp. 437-450. 1933.

No. 32. H. R. Seiwell. The Distribution of Oxygen in the Western Basin of the North Atlantic. *Papers in Physical Oceanography and Meteorology*, Vol. III, No. 1, 86 pp. 1934.

No. 33. George L. Clarke. Diurnal Migration of Plankton in the Gulf of Maine and its Correlation with Changes in Submarine Irradiation. *Biol. Bull.*, Vol. LXV, pp. 402-435. 1933.

No. 34. Henry B. Bigelow. Studies of the Waters on the Continental Shelf, Cape Cod to Chesapeake Bay. I. The Cycle of Temperature. *Papers in Physical Oceanography and Meteorology*, Vol. II, No. 4, 135 pp. 1933.

No. 35. Albert Eide Parr. Report on Experimental Use of a Triangular Trawl for Bathypelagic Collecting. *Bull. Bingham Oceanographic Coll.*, Vol. IV, Art. 6, pp. 1-59. 1934.

No. 36. G. H. Parker and Helen Porter. The control of the Dermal Melanophores in Elasmobranch Fishes. *Biol. Bull.*, Vol. LXVI, pp. 30-37. 1934.

No. 37. G. H. Parker. The Color Changes of Elasmobranch Fishes. *Proc. Nat. Acad. Sci.*, Vol. 19, pp. 1038-1039. 1933.

No. 38. Raymond W. Root. The Combination of Carbon Monoxide with Hemocyanin. *Jour. Biol. Chem.*, Vol. 104, No. 2, pp. 239-244. 1934.

No. 39. Selman A. Waksman. The Distribution and Conditions of Existence of Bacteria in the Sea. *Ecological Monographs*, Vol. 4, No. 4, pp. 523-529. 1934.

No. 40. G. L. Clarke. The Rôle of Copepods in the Economy of the Sea. *Fifth Pacific Science Congress*, Vancouver, B. C., a 5.5, pp. 2017-2021. 1934.

No. 41. George L. Clarke. Factors Affecting the Vertical Distribution of Copepods. *Ecological Monographs*, Vol. 4, No. 4, pp. 530-540. 1934.

No. 42. Philip H. Mitchell and Julian L. Solinger. The Effects of Land Drainage upon the Excess Bases of Sea Water. *Biol. Bull.*, Vol. LXVI, No. 2, pp. 97-101. 1934.

No. 43. Selman A. Waksman, Cornelia L. Carey and Melvin C. Allen. Bacteria Decomposing Alginic Acid. *Jour. Bacteriology*, Vol. 28, No. 2, pp. 213-220. 1934.

No. 44. Cornelia L. Carey and Selman A. Waksman. The Presence of Nitrifying Bacteria in Deep Seas. *Science*, Vol. 79, No. 2050, pp. 349-350. 1934.

No. 45. G. L. Clarke and R. H. Oster. The Penetration of the Blue and Red Components of Daylight into Atlantic Coastal Waters and its Relation to Phytoplankton Metabolism. *Biol. Bull.*, Vol. LXVII, No. 1, pp. 59-75. 1934.

No. 46. Trygve Braarud. A Note on the Phytoplankton of the Gulf of Maine in the Summer of 1933. *Biol. Bull.*, Vol. LXVII, No. 1, pp. 76-82. 1934.

No. 47. August Krogh and Ancel Keys. Methods for the Determination of Dissolved Organic Carbon and Nitrogen in Sea Water. *Biol. Bull.*, Vol. LXVII, No. 1, pp. 132-144. 1934.

No. 48. George L. Clarke. Further Observations on the Diurnal Migration of Copepods in the Gulf of Maine. *Biol. Bull.*, Vol. LXVII, No. 3, pp. 432-455. 1934.

No. 49. Phil E. Church. Surface-Temperatures on the New York to Cape São Roque Steamship-Route. *Trans. Am. Geophys. Union, Fifteenth Annual Meeting*, pp. 204-208. 1934.

No. 50. Raymond W. Root and Arda Alden Green. The Effect of Acidity on the Carbon Monoxide-Combining Power of Hemoglobin in the Blood of Marine Fishes. *Jour. Biol. Chem.*, Vol. 106, No. 2, pp. 545-552. 1934.

No. 51. C. O'D. Iselin. Temperature-Salinity Correlation within the Florida Current. *Trans. Am. Geophys. Union, Fifteenth Annual Meeting*, pp. 208-209. 1934.

No. 52. H. C. Stetson and Marshall Schalk. Marine Erosion of Glacial Deposits in Massachusetts Bay. *Jour. Sedimentary Petrology*, Vol. 5, No. 1, pp. 40-51. 1935.

No. 53. Charles E. Renn. Wasting Disease of Zostera in American Waters. *Nature*, Vol. 134, p. 416. 1934.

No. 54. George L. Clarke. The Diurnal Migration of Copepods in St. Georges Harbor, Bermuda. *Biol. Bull.*, Vol. LXVII, No. 3, pp. 456-460. 1934.

No. 55. F. A. Brown, Jr. The Chemical Nature of the Pigments and the Transformations Responsible for Color Changes in Palaemonetes. *Biol. Bull.*, Vol LXVII, No. 3, pp. 365-380. 1934.

No. 56. R. M. Bond. Digestive Enzymes of the Pelagic Copepod, *Calanus finmarchicus*. *Biol. Bull.*, Vol. LXVII, No. 3, pp. 461-465. 1934.

No. 57. Selman A. Waksman and Cornelia L. Carey. Decomposition of Organic Matter in Sea Water by Bacteria. I. Bacterial Multiplication in Stored Sea Water. *Jour. Bacteriology*, Vol. 29, No. 5, pp. 531-543. 1935.

No. 58. R. H. Oster and G. L. Clarke. The Penetration of the Red, Green and Violet Components of Daylight into Atlantic Waters. *Jour. Optical Soc. Amer.*, Vol. 25, No. 3, pp. 1-16. 1935.

No. 59. Benjamin B. Leavitt. A Quantitative Study of the Vertical Distribution of the Larger Zoöplankton in Deep Water. *Biol. Bull.*, Vol. LXVIII, No. 1, pp. 115-130. 1935.

No. 60. G. H. Parker. The Electric Stimulation of Chromatophoral Nerve-Fibers in the Dogfish. *Biol. Bull.*, Vol. LXVIII, No. 1, pp. 1-3. 1935.

No. 61. Henry B. Bigelow and W. C. Schroeder. Canadian Atlantic Fauna. 12. Chordata; 12d. Marsipobranchii (Lampreys); 12e. Elasmobranchii (Sharks and Rays); 12f. Holocephali (Chimaeroids). *Biological Board of Canada*. pp. 1-38. 1934.

No. 62. In preparation.

No. 63. Gladys Eddy Seiwell. Note on Iron Analyses of Atlantic Coastal Waters. *Ecology*, Vol. XVI, No. 4, pp. 663-664. 1935.

No. 64. H. R. Seiwell. The Phosphorus Cycle in the Western Basin of the North Atlantic. Part I. The Distribution of Phosphate and Organic Phosphorus. *Papers in Physical Oceanography and Meteorology*, Vol. 3, No. 4, pp. 1-56. 1935.

No. 65. James B. Lackey. Occurrence and Distribution of the Marine Protozoan Species in the Woods Hole Area. *Biol. Bull.*, Vol. LXX, No. 2, pp. 264–278. 1936.

No. 66. G. L. Clarke and S. S. Gellis. The Nutrition of Copepods in Relation to the Food-Cycle of the Sea. *Biol. Bull.*, Vol. LXVIII, No. 2, pp. 231-246. 1935.

No. 67. Charles E. Renn. A Mycetozoan Parasite of *Zostera marina*. *Nature*. Vol. 135, p. 544. 1935.

No. 68. Selman A. Waksman and Cornelia L. Carey. Decomposition of Organic Matter in Sea Water by Bacteria. II. Influence of Addition of Organic Substances upon Bacterial Activities. *Jour. Bacteriology*, Vol. 29, No. 5, pp. 545-561. 1935.

No. 69. H. H. Gran and Trygve Braarud. A Quantitative Study of the Phytoplankton in the Bay of Fundy and the Gulf of Maine (including Observations on Hydrography, Chemistry and Turbidity). *Jour. Biol. Bd. Canada*, Vol. 1, No. 5, pp. 279-467. 1935.

No. 70. Henry B. Bigelow and Mary Sears. Studies on the Waters of the Continental Shelf, Cape Cod to Chesapeake Bay. II. Salinity. *Papers in Physical Oceanography and Meteorology*, Vol. 4, No. 1, pp. 1-94. 1935.

No. 71. C. G. Rossby and R. B. Montgomery. The Layer of Frictional Influence in Wind and Ocean Currents. *Papers in Physical Oceanography and Meteorology*, Vol. 3, No. 3, pp. 1-101. 1935.

No. 72. In preparation.

No. 73. F. K. Sparrow, Jr. The Occurrence of Saprophytic Fungi in Marine Muds. *Biol. Bull.*, Vol. LXXIII, No. 2, pp. 242-248. 1937.

No. 74. Philip H. Mitchell and Ivon R. Taylor. The Dissociation Constant of Cresol Red in Sea Water. *Jour. d. Conseil*, Vol. 10, No. 2, pp. 169-172. 1935.

No. 75. L. Irving, D. Y. Solandt and O. M. Solandt. Nerve Impulses from Branchial Pressure Receptors in the Dogfish. *Jour. Physiol.* Vol. 84, No. 2, p. 187. 1935.

No. 76. H. C. Stetson. Bed-Rock from the Continental Margin on Georges Bank. *Trans. Am. Geophys. Union, Sixteenth Annual Meeting*, pp. 226-228. 1935.

No. 77. H. R. Seiwell. Phosphate in the Western Basin of the North Atlantic. *Nature*, Vol. 136, p. 206. 1935.

No. 78. Selman A. Waksman and Charles E. Renn. Decomposition of Organic Matter in Sea Water by Bacteria. III. Factors Influencing the Rate of Decomposition. *Biol. Bull.*, Vol. LXX, No. 3, pp. 472–483. 1936.

No. 79. Ancel Keys, E. H. Christensen, and August Krogh. The Organic Metabolism of Sea-water with Special Reference to the Ultimate Food Cycle in the Sea. *Jour. Marine Biol. Assoc.*, Vol. XX, No. 2, pp. 181-196. 1935.

No. 80. Henry C. Stetson. Geology and Paleontology of the Georges Bank Canyons. I. Geology. *Bull. Geol. Soc. Amer.*, Vol. 47, pp. 339–366. 1936.

No. 81. Lloyd William Stephenson. Geology and Paleontology of the Georges Bank Canyons. II. Upper Cretaceous Fossils from Georges Bank (including Species from Banquereau, Nova Scotia). *Bull. Geol. Soc. Amer.*, Vol. 47, pp. 367–410. 1936.

No. 82. Joseph A. Cushman. Geology and Paleontology of the Georges Bank Canyons. IV. Cretaceous and Late Tertiary Foraminifera. *Bull. Geol. Soc. Amer.*, Vol. 47, pp. 413–440. 1936.

No. 83. George Wald. Pigments of the Retina. II. Sea Robin, Sea Bass, and Scup. *Jour. Gen. Physiol.*, Vol. 20, No. 1, pp. 45–56. 1936.

No. 84. R. S. Bassler. Geology and Paleontology of the Georges Bank Canyons. III. Cretaceous Bryozoan from Georges Bank. *Bull. Geol. Soc. Amer.*, Vol. 47, pp. 411–412. 1936.

No. 85. Charles J. Fish. The Biology of *Calanus finmarchicus* in the Gulf of Maine and Bay of Fundy. *Biol. Bull.* Vol. LXX, No. 1, pp. 118–141. 1936.

No. 86. Norris W. Rakestraw, Henry E. Mahncke and Eliot F. Beach. Determination of Iron in Sea Water. *Analytical edition Ind. and Eng. Chem.*, Vol. 8, pp. 136–138. 1936.

No. 87. Norris W. Rakestraw and Henry E. Mahncke. Boron Content of Sea Water of the North Atlantic Coast. *Analytical edition Ind. and Eng. Chem.*, Vol. 7, p. 425. 1935.

No. 88. E. E. Watson. Mixing and Residual Currents in Tidal Waters as Illustrated in the Bay of Fundy. *Jour. Biol. Bd. Canada*, 2 (2), pp. 141–208. 1936.

No. 89. George Wald. The Visual Purple System in Marine Fishes. *Nature*, Vol. 136, p. 913. 1935.

No. 90. Charles E. Renn. The Wasting Disease of *Zostera marina*. I. A Phytological Investigation of the Diseased Plant. *Biol. Bull.*, Vol. LXX, No. 1, pp. 148–158. 1936.

No. 91. S. Edward Roos. Some Geographical Results of the Second Byrd Antarctic Expedition, 1933-1935. I. The Submarine Topography of the Ross Sea and Adjacent Waters. *Geog. Rev.*, Vol. XXVII, No. 4, pp. 574-583. 1937.

No. 92. John L. Fuller and George L. Clarke. Further Experiments on the Feeding of *Calanus finmarchicus*. *Biol. Bull.*, Vol. LXX, No. 2, pp. 308-320. 1936.

No. 93. Maurice Ewing, A. P. Crary, and H. M. Rutherford. Geophysical Investigations in the Emerged and Submerged Atlantic Coastal Plain. I. Methods and Results. *Bull. Geol. Soc. Amer.*, Vol. 48, pp. 753-802. 1937.

No. 94. Charles J. Fish. The Biology of *Pseudocalanus minutus* in the Gulf of Maine and Bay of Fundy. *Biol. Bull.*, Vol. LXX, No. 2, pp. 193–216. 1936.

No. 95. Frank H. Johnson. The Oxygen Uptake of Marine Bacteria. *Jour. Bacteriology*, Vol. 31, No. 5, pp. 547–556. 1936.

No. 96. Michael Graham. Investigations of the Herring of Passamaquoddy and Adjacent Regions. *Jour. Biol. Bd. Canada*, 2 (2), pp. 95–140. 1936.

No. 97. A. E. Parr. On the Probable Relationship Between Vertical Stability and Lateral Mixing Processes. *Jour. d. Conseil*, Vol. XI, No. 3, pp. 299–313. 1936.

No. 98. Wilson M. Powell and George L. Clarke. The Reflection and Absorption of Daylight at the Surface of the Ocean. *Jour. Optical Soc. Amer.*, Vol. 26, pp. 1–23. 1936.

No. 99. F. K. Sparrow, Jr. Biological Observations on the Marine Fungi of Woods Hole Waters. *Biol. Bull.*, Vol. LXX, No. 2, pp. 236–263. 1936.

No. 100. George L. Clarke. On the Depth at which Fish Can See. *Ecology*, Vol. 17, No. 3, pp. 452–456. 1936.

No. 101. George L. Clarke. Light Penetration in the Western North Atlantic and its Application to Biological Problems. *Rapp. et Proc. Verb. Cons. Perm. Internat. Exp. Mer.*, Vol. 101, Pt. 2, pp. 1–14. 1936.

No. 102. C.-G. Rossby and R. B. Montgomery. I. On the Frictional Force between Air and Water and on the Occurrence of a Laminar Boundary Layer next to the Surface of the Sea. C.-G. Rossby. II. Measurements of Vertical Gradient of Wind over Water. R. B. Montgomery. III. Transport of Surface Water due to the Wind System over the North Atlantic. R. B. Montgomery. *Papers In Physical Oceanography and Meteorology*, Vol. 4, No. 3, pp. 1–101. 1936.

No. 103. H. C. Stetson. Dredge-Samples from the Submarine Canyons between the Hudson Gorge and Chesapeake Bay. *Trans. Am. Geophys. Union, Seventeenth Annual Meeting*, pp. 223–225. 1936.

No. 104. Columbus Iselin. The Influence of the Mediterranean Outflow at Mid-Depths in the Sargasso Sea. *Trans. Am. Geophys. Union, Seventeenth Annual Meeting*, pp. 219–221. 1936.

No. 105. R. B. Montgomery. Computation of the Transport of Surface-Water due to the Wind-System over the North Atlantic. *Trans. Am. Geophys. Union, Seventeenth Annual Meeting*, pp. 225–229. 1936.

No. 106. Margaret Hotchkiss and Selman A. Waksman. Correlative Studies of Microscopic and Plate Methods for Evaluating the Bacterial Population of the Sea. *Jour. Bacteriology*, Vol. 32, No. 4, pp. 423–432. 1936.

No. 107. Edward H. Smith, Floyd M. Soule, Olav Mosby. The "Marion" and "General Greene" Expeditions to Davis Strait and Labrador Sea under Direction of the United States Coast Guard 1928-1931-1933-1934-1935. Scientific Results. Part 2. Physical Oceanography. *U. S. Coast Guard Bull.*, No. 19, pp. I-VI, pp. 1–259. 1937.

No. 108. Columbus Iselin. Study of the Circulation of the North Atlantic Ocean. *Papers in Physical Oceanography and Meteorology*, Vol. 4, No. 4, pp. 1-101. 1936.

No. 109. Charles J. Fish. The Biology of *Oithona similis* in the Gulf of Maine and Bay of Fundy. *Biol. Bull.*, Vol. LXXI, No. 1, pp. 168–187. 1936.

No. 110. Norris W. Rakestraw. The Occurence and Significance of Nitrite in the Sea. *Biol. Bull.*, Vol. LXXI, No. 1, pp. 133–167. 1936.

No. 111. Charles E. Renn. The Eel-Grass Situation along the Middle Atlantic Coast. *Ecology*, Vol. 18, No. 2, pp. 323-325. 1937.

No. 112. George L. Clarke and Donald J. Zinn. Seasonal Production of Zoöplankton off Woods Hole with Special Reference to *Calanus finmarchicus*. *Biol. Bull.*, Vol. LXXIII, No. 3, pp. 464–487. 1937.

No. 113. G. H. Parker. The Reactivation by Cutting of Severed Melanophore Nerves in the Dogfish Mustelus. *Biol. Bull.*, Vol. LXXI, No. 2, pp. 255–258. 1936.

No. 114. PHILIP H. MITCHELL, KURT BUCH and NORRIS W. RAKESTRAW. The Effect of Salinity and Temperature upon the Dissociation of Cresol Red and Phenol Red in Sea Water. *Jour. d. Conseil*, Vol. XI, No. 2, pp. 183–189. 1936.

No. 115. C.-G. ROSSBY. Dynamics of Steady Ocean Currents in the Light of Experimental Fluid Mechanics. *Papers in Physical Oceanography and Meteorology*, Vol. 5, No. 1, pp. 1–43. 1936.

No. 116. CHARLES P. WINSOR and LIONEL A. WALFORD. Sampling Variations in the Use of Plankton Nets. *Jour. d. Conseil*, Vol. XI, No. 2, pp. 190–204. 1936.

No. 117. CHARLES E. RENN. Persistence of the Eel-Grass Disease and Parasite on the American Atlantic Coast. *Nature*, Vol. 138, p. 507. 1936.

No. 118. H. R. SEIWELL. Relationship of Minimum Oxygen Concentration to Density of the Water Column in the Western North Atlantic. *Gerlands Beiträge zur Geophysik*, Vol. 50, pp. 302–306. 1937.

No. 119. HENRY B. BIGELOW and WILLIAM C. SCHROEDER. Supplemental Notes on Fishes of the Gulf of Maine. *Bull. Bur. Fisheries*, Vol. XLVIII, Bull. No. 20, pp. 319–343. 1936.

No. 120. NORRIS W. RAKESTRAW and ALEXANDER HOLLAENDER. Photochemical Oxidation of Ammonia in Sea Water. *Science*, Vol. 84, No. 2185, pp. 442–443. 1936.

No. 121. PHIL E. CHURCH. Temperatures of the Western North Atlantic from Thermograph Records. *Publ. Scientifique*, No. 4, pp. 1–32. 1937.

No. 122. ALFRED C. REDFIELD. An Ecological Aspect of the Gulf Stream. *Nature*, Vol. 138, p. 1013. 1936.

No. 123. THEODOR VON BRAND. Observations upon the Nitrogen of the Particulate Matter in the Sea. *Biol. Bull.*, Vol. LXXII, No. 1, pp. 1–6. 1937.

No. 124. SELMAN A. WAKSMAN and MARGARET HOTCHKISS. Viability of Bacteria in Sea Water. *Jour. Bacteriol.*, Vol. 33, No. 4, pp. 389–400. 1937.

No. 125. ALBERT EIDE PARR. A Contribution to the Hydrography of the Caribbean and Cayman Seas. Based upon the observations made by the Research Ship "Atlantis", 1933–34. *Bull. Bingham Oceanographic Coll.*, Vol. V, Art. 4, pp. 1–110. 1937.

No. 126. J. H. WELSH and F. A. CHACE, JR. Eyes of Deep Sea Crustaceans. I. Acanthephyridae *Biol. Bull.*, Vol. LXXII, No. 1, pp. 57–74. 1937.

No. 127. ALFRED C. REDFIELD, HOMER P. SMITH and BOSTWICK KETCHUM. The Cycle of Organic Phosphorus in the Gulf of Maine. *Biol. Bull.*, Vol. LXXIII, No. 3, pp. 421–443. 1937.

No. 128. WILLIAM F. WRATH. Contamination and Compaction on Core Sampling. *Science*, Vol. 84, No. 1289, pp. 537–538. 1936.

No. 129. THEODOR VON BRAND, NORRIS W. RAKESTRAW and CHARLES E. RENN. The Experimental Decomposition and Regeneration of Nitrogenous Organic Matter in Sea Water. *Biol. Bull.*, Vol. LXXII, No. 2, pp. 165-175. 1937.

No. 130. H. C. STETSON and J. E. UPSON. Bottom Deposits of the Ross Sea. *Jour. Sedimentary Petrology*, Vol. 7, No. 2, pp. 55–66. 1937.

No. 131. G. H. Parker. Integumentary Color Changes of Elasmobranch Fishes Especially of Mustelus. *Proc. Am. Philos. Soc.*, Vol. 77, No. 3, pp. 223–247. 1937.

No. 132. John L. Fuller. Feeding Rate of *Calanus finmarchicus* in Relation to Environmental Conditions. *Biol. Bull.*, Vol. LXXII, No. 2, pp. 233–246. 1937.

No. 133. Charles E. Renn. Bacteria and the Phosphorus Cycle in the Sea. *Biol. Bull.*, Vol. LXXII, No. 2, pp. 190–195. 1937.

No. 134. Robert C. Stauffer. Changes in the Invertebrate Community of a Lagoon after Disappearance of the Eel Grass. *Ecology*, Vol. 18, No. 3, pp. 427–431. 1937.

No. 135. Charles J. Fish and Martin W. Johnson. The Biology of the Zoöplankton Population in the Bay of Fundy and Gulf of Maine with Special Reference to Production and Distribution. *J. Biol. Bd. Can.*, Vol. 3, No. 3, pp. 189–322. 1937.

No. 136. Marshall Schalk. A Textural Study of the Outer Beach of Cape Cod, Massachusetts. *Jour. Sedimentary Petrology*, Vol. 8, No. 2, pp. 41-54. 1938.

No. 137. H. R. Seiwell. Short Period Vertical Oscillations in the Western Basin of the North Atlantic. *Papers in Physical Oceanography and Meteorology*, Vol. V, No. 2, pp. 1–44. 1937.

No. 138. H. R. Seiwell. The Minimum Oxygen Concentration in the Western Basin of the North Atlantic. *Papers in Physical Oceanography and Meteorology*, Vol. V, No. 3, pp. 1–24. 1937.

No. 139. H. R. Seiwell. The Oxygen-Poor Layer in the Western North Atlantic. *Jour. d. Conseil*, Vol. XII, No. 3, pp. 277–283. 1937.

No. 140. Norris W. Rakestraw and Homer P. Smith. A Contribution to the Chemistry of the Caribbean and Cayman Seas. *Bull. Bingham Oceanographic Coll.*, Vol. VI, Art. 1, pp. 1–41. 1937.

No. 141. Norris W. Rakestraw and Victor M. Emmel. The Determination of Dissolved Nitrogen in Water. *Analytical edition Ind. and Eng. Chem.*, Vol. 9, pp. 1–6. 1937.

No. 142. H. R. Seiwell. Short-Period Variations of Oceanographic Characteristics in the Western North Atlantic. *Trans. Am. Geophys. Union, Eighteenth Annual Meeting*, pp. 220–222. 1937.

No. 143. H. C. Stetson. Current-Measurements in the Georges Bank Canyons. *Trans. Am. Geophys. Union, Eighteenth Annual Meeting*, pp. 216–219. 1937.

No. 144. Margaret Ruth Butler. The Effect of its Nitrogen Content on the Decomposition of the Polysaccharide Extract of *Chondrus crispus*. *Biol. Bull.*, Vol. LXXIII, No. 1, pp. 143–146. 1937.

No. 145. J. H. Welsh, F. A. Chace, Jr., and R. F. Nunnemacher. The Diurnal Migration of Deep-Water Animals. *Biol. Bull.*, Vol. LXXIII, No. 2, pp. 185-196. 1937.

No. 146. H. C. Stetson and J. Fred Smith. Behavior of Suspension Currents and Mud Slides on the Continental Slope. *Am. Jour. Sc.*, *Fifth Series*, Vol. XXXV, No. 205, pp. 1–13. 1937.

No. 147. Henry B. Bigelow. Plankton of the Bermuda Oceanographic Expeditions. VIII. Medusae taken during the Years 1929 and 1930. *Zoologica*, Vol. XXIII, No. 5, pp. 99-189. 1938.

No. 148. Abby H. Turner. Serum Protein Measurements in the Lower Vertebrates. II. In Marine Teleosts and Elasmobranchs. *Biol. Bull.*, Vol. LXXIII, No. 3, pp. 511–526. 1937.

No. 149. Albert Eide Parr. On the Longitudinal Variations in the Dynamic Elevation of the Surface of the Caribbean Current. *Bull. Bingham Oceanographic Coll.*, Vol. VI, Art. 2, pp. 1–20. 1937.

No. 150. Gordon A. Riley. The Significance of the Mississippi River Drainage for Biological Conditions in the Northern Gulf of Mexico. *Sears Found. Jour. Mar. Res.*, Vol. I, No. 1, pp. 60–74. 1937.

No. 151. H. R. Seiwell. Consumption of Oxygen in Sea Water under Controlled Laboratory Conditions. *Nature*, Vol. 140, p. 506. 1937.

No. 152. H. R. Seiwell and Gladys Eddy Seiwell. The Sinking of Decomposing Plankton in Sea Water and its Relationship to Oxygen Consumption and Phosphorus Liberation. *Proc. Am. Philos. Soc.*, Vol. 78, No. 3, pp. 465–481. 1938.

No. 153. R. B. Montgomery. A Suggested Method for Representing Gradient Flow in Isentropic Surfaces. *Bull. Am. Meteorol. Soc.*, Vol. 18, pp. 210–212. 1937.

No. 154. Floyd M. Soule. Oceanography. Excerpt from International Ice Observation and Ice Patrol Service in the North Atlantic Ocean, Season of 1936. *U. S. Coast Guard Bull.*, No. 26, pp. 33-82. 1938.

No. 155. Albert Eide Parr. Report on Hydrographic Observations at a Series of Anchor Stations across the Straits of Florida. *Bull. Bingham Oceanographic Coll.*, Vol. VI, Art. 3, pp. 1–62. 1937.

No. 156. Lois C. Lillick. Seasonal Studies of the Phytoplankton off Woods Hole, Massachusetts. *Biol. Bull.*, Vol. LXXIII, No. 3, pp. 488–503. 1937.

No. 157. Selman A. Waksman, J. L. Stokes and Margaret R. Butler. Relation of Bacteria to Diatoms in Sea Water. *Jour. Mar. Biol. Assoc.*, Vol. XXII, pp. 359–373. 1937.

No. 158. Athelstan F. Spilhaus. Note on the Flow of Streams in a Rotating System. *Sears Found. Jour. Mar. Res.*, Vol. I, No. 1, pp. 29–33. 1937.

No. 159. Alfred C. Redfield and Ancel B. Keys. The Distribution of Ammonia in the Waters of the Gulf of Maine. *Biol. Bull.*, Vol. LXXIV, No. 1, pp. 83–92. 1938.

No. 160. Selman A. Waksman, Margaret Hotchkiss, Cornelia L. Carey and Y. Hardman. Decomposition of Nitrogenous Substances in Sea Water by Bacteria. *Jour. Bacteriology*, Vol. 35, No. 5, pp. 477-486. 1938.

No. 161. Selman A. Waksman and Unto Vartiovaara. The Adsorption of Bacteria by Marine Bottom. *Biol. Bull.* Vol. LXXIV, No. 1, pp. 56–63. 1938.

No. 162. H. R. Seiwell. Application of the Distribution of Oxygen to the Physical Oceanography of the Caribbean Sea Region. *Papers in Physical Oceanography and Meteorology*, Vol. VI, No. 1, pp. 1-60. 1938.

No. 163. Theodor von Brand. Quantitative Determination of the Nitrogen in the Particulate Matter of the Sea. *Jour. d. Conseil*, Vol. XII, No. 2, pp. 187-196. 1938.

No. 164. George L. Clarke. On Securing Large Quantities of Diatoms from the Sea for Chemical Analysis. *Science*, Vol. 86, No. 2243, pp. 593–594. 1937.

No. 165. Selman A. Waksman and Margaret Hotchkiss. On the Oxidation of Organic Matter in Marine Sediments by Bacteria. *Sears Found. Jour. Mar. Res.*, Vol. I, No. 2, pp. 101-118. 1938.

No. 166. George L. Clarke. Seasonal Changes in the Intensity of Submarine Illumination off Woods Hole. *Ecology*, Vol. 19, No. 1, pp. 89–106. 1938.

No. 167. Athelstan F. Spilhaus. A Bathythermograph. *Sears Found. Jour. Mar. Res.*, Vol. I, No. 2, pp. 95-100. 1938.

No. 168. George L. Clarke. Light Penetration in the Caribbean Sea and in the Gulf of Mexico. *Sears Found. Jour. Mar. Res.*, Vol. I, No. 2, pp. 85-94. 1938.

No. 169. H. C. Stetson. Present Status of the Problem of Submarine Canyons. *Proc. Amer. Philos. Soc.*, Vol. 79, No. 1, pp. 27-33. 1938.

No. 170. R. B. Montgomery. Fluctuations in Monthly Sea Level on Eastern U. S. Coast as Related to Dynamics of Western North Atlantic Ocean. *Sears Found. Jour. Mar. Res.*, Vol. I, No. 2, pp. 165-185. 1938.

No. 171. C. O'D. Iselin. The influence of Fluctuations in the Major Ocean Current on the Climate and the Fisheries. *The Collecting Net*, Vol. XIII, No. 7, pp. 1-4. 1938.

No. 172. Bostwick H. Ketchum and Alfred C. Redfield. A Method for Maintaining a Continuous Supply of Marine Diatoms by Culture. *Biol. Bull.* Vol. LXXV, No. 1, pp. 165-169. 1938.

No. 173. In preparation.

No. 174. Benjamin B. Leavitt. The Quantitative Vertical Distribution of Macrozoöplankton in the Atlantic Ocean Basin. *Biol. Bull.*, Vol. LXXIV, No. 3, pp. 376-394. 1938.

No. 175. Norris W. Rakestraw and Victor M. Emmel. The Solubility of Nitrogen and Argon in Sea Water. *Jour. Phys. Chem.*, Vol. 42, No. 9, pp. 1211-1215. 1938.

No. 176. J. H. Welsh and F. A. Chace, Jr. Eyes of Deep-Sea Crustaceans II. Sergestidae. *Biol. Bull.*, Vol. LXXIV, No. 3, pp. 364-375. 1938.

No. 177. H. R. Seiwell. Eddy Diffusion at Mid-Depths in the Carribbean Sea Region. *Jour. d. Conseil.*, Vol. XIII, No. 2, pp. 155-162. 1938.

No. 178. H. C. Stetson. The Sediments of the Continental Shelf off the Eastern Coast of the United States. *Papers in Physical Oceanography and Meteorology*, Vol. V, No. 4, pp. 1-48. 1938.

No. 179. Albert Eide Parr. Further Observations on the Hydrography of the Eastern Caribbean and Adjacent Atlantic Waters. *Bull. Bingham Oceanographic Coll.*, Vol. 6, Art. 4, pp. 1-29. 1938.

No. 180. C. O'D. Iselin. A Promising Theory Concerning the Causes and Results of Long-Period Variations in the Strength of the Gulf Stream System. *Trans. Am. Geophys. Union, Nineteenth Annual Meeting*, pp. 243-244. 1938.

No. 181. H. R. Seiwell. Use of Non-Conservative Properties of Sea Water to Physical Oceanographical Problems. *Nature*, Vol. 142, p. 164. 1938.

No. 182. Norris W. Rakestraw and Victor M. Emmel. The Relation of Dissolved Oxygen to Nitrogen in Some Atlantic Waters. *Sears Found. Jour. Mar. Res.*, Vol. I, No. 3, pp. 207-216. 1938.

No. 183. W. H. Johnson. The Effect of Light on the Vertical Movements of *Acartia clausi* (Giesbrecht). *Biol. Bull.*, Vol. LXXV, No. 1, pp. 106-118. 1938.

No. 184. In preparation.

No. 185. C.-G. Rossby. On the Mutual Adjustment of Pressure and Velocity Distributions in Certain Simple Current Systems, II. *Sears Found. Jour. Mar. Res.*, Vol. I, No. 3, pp. 239-263. 1938.

No. 186. H. R. Seiwell. Über die ganz- und halbtägige Mondkomponente der internen Wellen im westlichen Nordatlantischen Ozean. *Annalen der Hydrographie u. maritimen Meteorologie*, Heft X, pp. 485-487. 1938.

No. 187. In preparation.

No. 188. Cornelia L. Carey. The Occurrence and Distribution of Nitrifying Bacteria in the Sea. *Sears Found. Jour. Mar. Res.*, Vol. I, No. 4, pp. 291-304. 1938.

No. 189. Lois C. Lillick. Preliminary Report of the Phytoplankton of the Gulf of Maine. *The Amer. Midland Nat.*, Vol. 20, No. 3, pp. 624-640. 1938.

No. 190. R. B. Montgomery. Circulation in Upper Layers of Southern North Atlantic Deduced with Use of Isentropic Analysis. *Papers in Physical Oceanography and Meteorology*, Vol. VI, No. 2, pp. 1-55. 1938.

No. 191. In preparation.

No. 192. In preparation.

No. 193. In preparation.

No. 194. In preparation.

No. 195. George Wald. On the Distribution of Vitamins A_1 and A_2. *Jour. Gen. Physiol.*, Vol. 22, No. 3, pp. 391-415. 1939.

No. 196. In preparation.

No. 197. In preparation.

No. 198. W. J. Clench and C. G. Aguayo. Notes and Descriptions of New Species of Calliostoma, Gaza and Columbarium (Mollusca); Obtained by the Harvard-Habana Expedition off the Coast of Cuba. *Mem. Soc. Cub. Hist. Nat.*, Vol. 12, No. 5, pp. 375-384. 1938.

No. 199. In preparation.

No. 200. Pedro J. Bermúdez. Resultados de la Primera Expedicion en las Antillas del Ketch Atlantis bajo los Auspicios de las Universidades de Harvard y Habana. *Mem. Soc. Cub. Hist. Nat.*, Vol. 12, No. 5, pp. 385-388. 1938.

No. 201. In preparation.

No. 202. In preparation.

No. 203. Martin D. Burkenroad. Further Observations on Penaeidae of the Northern Gulf of Mexico. *Bull. Bing. Oceanographic Coll.*, Vol. VI, Art. 6, pp. 1-62. 1939.